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Anatomic intra-articular reconstruction of the cranial cruciate ligament in dogs: The femoral tunnel

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Meiner Familie und meinen Freunden

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ABBREVIATIONS

ACL	Anterior Cruciate Ligament
CaCL	Caudal Cruciate Ligament
CrCL	Cranial Cruciate Ligament
CT	Computed Tomography
DJD	Degenerative Joint Disease
LFTS	Lateral Fabello-Tibial Suture
MRI	Magnetic Resonance Imaging
TPLO	Tibial Plateau Leveling Osteotomy
TTA	Tibial Tuberosity Advancement

1 Introduction

Cranial cruciate ligament (CrCL) pathology is the most frequent cause of hindlimb lameness in middle to large breed dogs (JOHNSON et al. 1994). The aetiopathogenesis of this multifactorial disease is not fully understood, and remains a controversial topic in the veterinary literature (MOORE and READ 1995, DOOM et al. 2008, COMERFORD et al. 2011). Epidemiologic factors such as breed predisposition or anatomic features of the hind limb also play a role and are reported as potential risk factors (COMERFORD et al. 2011). Degeneration of the CrCL leads to either partial or complete rupture of the CrCL with subsequent cranio-caudal and rotational stifle instability (ARNOCZKY and MARSHALL 1977, KORVICK et al. 1994b) leading to the so called ‘drawer movement’. Joint instability leads to permanent inflammation, cartilage erosions, osteoarthritis (TIRGARI 1978) and, in 52-70 % of the cases damage to the caudal horn of the medial meniscus (RALPHS and WHITNEY 2002, TIVERS et al. 2009, BOTTCHER et al. 2010).

The CrCL originates on the axial aspect of the lateral femoral condyle, very close to the articular margin. It extends diagonally across the joint space and attaches to the cranial intercondylar area of the tibial plateau (SINGLETON 1957, ARNOCZKY and MARSHALL 1977). Two demonstrably separate bundles are apparent (ZAHM 1965, GIRGIS et al. 1975, ARNOCZKY and MARSHALL 1977, HEFFRON and CAMPBELL 1978, DE ROOSTER et al. 2006). These components are termed caudo-lateral and cranio-medial bundle, based on their relative attachment sites at the tibial plateau. The caudo-lateral, is taught during extension and loose during flexion and the cranio-medial, is taught during extension and flexion (ARNOCZKY and MARSHALL 1977, PROFFEN et al. 2012). The CrCL contributes to passive restraint of the stifle by limiting cranial translation of the tibia relative to the femur, excessive internal rotation of the tibia, and hyperextension of the stifle, as shown by *in vitro* biomechanical studies (ARNOCZKY and MARSHALL 1977). The results of an *in vivo* kinematic study (TASHMAN et al. 2004) do not 100% correlate with the *in vitro* results. The cranial tibial translation and the internal tibial rotation were confirmed. Interestingly, and in contrast to the study of Arnosczky (ARNOCZKY and MARSHALL 1977), the maximal tibial translation takes place during the stance phase of the gait cycle but not in flexion. Moreover an increase in the range of adduction/abduction was documented *in vivo* (TASHMAN et al. 2004). Finally, while in cadavers the transection of the CrCL leads to stifle hyperextension, clinically the limb is hold in a more flexed position. This reaction is considered adaptive to reduce pain while unloading the limb and probably eliminating joint instability (TASHMAN et al. 2004).

Diagnosis

The positive cranial drawer test is used to confirm the complete CrCL rupture, however, in cases with partial CrCL rupture, the diagnosis is not straightforward. The radiographic examination of the stifle is routinely used to diagnose the extent of concomitant degenerative joint disease (DJD), to exclude other pathologies and to support the tentative clinical diagnosis. Other imaging tools include magnetic resonance imaging (MRI) (BLOND et al. 2008, BARRETT et al. 2009, BOTTCHER et al. 2010), computed tomography (CT) with intra-articular contrast medium injection (TIVERS et al. 2008) and ultrasonography (ARNAULT et al. 2009). Usually the definitive diagnosis and inspection of the menisci are performed during arthrotomy or arthroscopy (MAHN et al. 2005, POZZI et al. 2008).

Although, arthroscopy is commonly performed by specialized veterinary surgeons, arthroscopic procedures are gaining popularity in small animals for diagnostic and therapeutic purposes (BEAL et al. 2003, MUIR 2010). Stifle arthroscopy in comparison to arthrotomy results in less morbidity, faster recovery, less postoperative pain, and a more optimal observation of the intra-articular structures, especially the caudal horn of the medial meniscus (WHITNEY 2003, HOELZLER et al. 2004, POZZI et al. 2008).

Therapy

The conservative therapy of the CrCL rupture includes restricted activity for at least 4 to 6 weeks, weight reduction in cases of adiposity and the use of nonsteroidal anti-inflammatory drugs (VASSEUR et al. 1987, ALTMAN 2010). Multimodal therapy also incorporates, exercise modification, rehabilitation, and dietary changes (ARGOFF 2002, BUDSBERG and BARTGES 2006, JOHNSTON et al. 2008). It has been shown that conservative treatment in dogs weighing <15kg can result in good clinical function (VASSEUR 1984). Despite these results most authors advise surgical stabilization of the joint, especially in middle to large breed dogs (BRINKER et al. 1990, TOBIAS and JOHNSTON 2011). The surgical therapy compared to the conservative treatment reduces the risk of secondary complications as DJD and meniscal tears (POND et al. 1970) as it aims for cranio-caudal stabilization of the stifle joint (POND et al. 1970). For these reasons the surgical therapy in dogs weighing more than 15 kg is considered the treatment of choice (POND and CAMPBELL 1972, VASSEUR 1984, SCHAFER and FLO 1998, FOSSUM 2007, TOBIAS and JOHNSTON 2011).

The available surgical procedures can be divided in three large groups: the intra-articular procedures, the extra-articular procedures and the dynamic stabilization techniques. The intra-articular procedures such as the one first described von Paatsama (PAATSAMA 1952) aim directly at reconstruction of the native CrCL to achieve stability. The extra-articular and dynamic stabilization methods address the joint instability indirectly by providing resistance to the cranio-caudal movement or by altering the forces applied to the joint, respectively. In the group of the extra-articular methods fibular head transposition (SMITH and TORG 1985) and lateral fabello-tibial suture (LFTS) (SCHAFER and FLO 1998) are the most representative examples. The dynamic stabilization methods, which are also known as tibial osteotomies (KIM et al. 2008), are mainly represented by the tibial plateau leveling osteotomy (TPLO) (SLOCUM and SLOCUM 1993), the tibial tuberosity advancement (TTA) (MONTAVON et al. 2002).

The overall most preferred and applied surgical method is the LFTS (KORVICK et al. 1994a, LEIGHTON 1999, DUERR et al. 2014). LFTS is relatively easy, has a high safety profile, does not require special instrumentation and is relatively cheap (MUIR 2010). In the veterinary literature there has been no differences in the outcomes of LFTS compared to the tibial osteotomies based on client-based and veterinarian-based subjective assessments, or muscle mass measures (MILLIS et al. 2008, AU et al. 2009, COOK et al. 2010, NELSON et al. 2013). On the other hand subjective results of a study showed that 87,5% of the dogs were clinically improved after LFTS, but just 60% of those animals were completely sound (MOORE and READ 1995). A more recent objective study, where gait analysis was used, showed that only just 40% of the dogs had a clinical improvement and only 14,9% of the cases showed a normal limb function (CONZEMIUS et al. 2005). Finally when comparing TPLO and LFTS, although the long terms outcomes have objectively shown to be similar (AU et al. 2009, NELSON et al. 2013), TPLO has shown to result in more symmetrical limb function in short term and faster recovery (NELSON et al. 2013).

The dynamic stabilization techniques are gaining popularity and new data show that TPLO is the most preferred surgical method among ACVS Diplomates in large breed dogs (DUERR et al. 2014). TPLO provides very good to excellent functional long-term results (GORDON-EVANS et al. 2013, NELSON et al. 2013). Moreover TPLO has shown to offer faster recovery and improved limb function in comparison to a commonly used extra-articular technique (capsular-fascial imbrication technique) (BODDEKER et al. 2012). Objective evaluation of limb use after TPLO via force plate and kinematic analysis has showed a good outcome after TPLO with improvement of ground reaction forces comparable to LFTS stabilization (CONZEMIUS et al. 2005, MILLIS et al. 2008). In a recent retrospective study up to 6.8 years after TPLO surgery, in 90.4% of all cases lameness results were judged excellent or good. Unfortunately TPLO is an invasive procedure associated with a high rate of postoperative complications. The complication rate varies in the literature between 10% and 34% (PACCHIANA et al. 2003, PRIDDY et al. 2003, STAUFFER et al. 2006, COLETTI et al. 2014). Although minor complications such as hemorrhage, seroma formation, superficial wound infection and patellar tendon enlargement predominate, major complications are not rare. Such complications include fractures involving the fibula or tibia, subsequent meniscal injury, osteomyelitis, implant failure. From those major complications 2 – 6 % require revision surgery (FITZPATRICK and SOLANO 2010, GATINEAU et al. 2011, BERGH and PEIRONE 2012).

Although the idea of advancing the tibial tuberosity is old (MAQUET 1976), TTA is a relatively new procedure and has shown to improve limb function, as confirmed by gait analysis (VOSS et al. 2008, MACDONALD et al. 2013). Unfortunately latest study results are rather disappointing. An *in vivo* study showed that femoral subluxation and therefore joint instability was reported in 70% of the dogs operated with TTA (SKINNER et al. 2013). Moreover TTA is associated with a relatively high number of complications reaching up to 59 % (HOFFMANN et al. 2006, LAFAVER et al. 2007, STEIN and SCHMOEKEL 2008). The biggest retrospective study has shown a complication rate of 19 % and interestingly 60 % of those complications were major (WOLF et al. 2012). Another significant drawback of the technique is the high rate of postoperative meniscal lesions (up to 27,8 %), being the most common reason for revision surgery after TTA (WOLF et al. 2012, CHRISTOPHER et al. 2013).

During intra-articular repair the CrCL is directly reconstructed with the use of biologic tissues, synthetic materials or a combination of both and fixed to the femoral and tibial insertion sites of the native ligament (TOBIAS and JOHNSTON 2011). Intra-articular CrCL reconstruction is at the moment one of the least preferred surgical methods (DUERR et al. 2014). Controversially, anatomic intra-articular reconstruction of the anterior cruciate ligament (ACL) remains the golden standard in humans (LEIGHTON 1999, MANLEY 2010, SCHINDLER 2012). In the veterinary medicine there is only one recent study directly comparing the intra-articular reconstruction to TPLO and LFTS (CONZEMIUS et al. 2005): Intra-articular reconstruction showed the worst clinical results. There are many possible explanations for the rare use of this method. Firstly, technical issues such as graft failure (VASSEUR et al. 1987), loss of integrity of the fixation points on the bone and non-anatomic positioning of the bone tunnels (HULSE et al. 1983, TOBIAS and JOHNSTON 2011) are discussed in the literature. In humans misplacement of either the femoral or tibial graft is the most common reason for revision surgery (NIKLAUS and MÜLLER 2000) and the smaller size of the canine stifle compared to the human knee joint makes the procedure a lot more technically difficult. Ligamentization and biologic incorporation of a soft-tissue graft to bone is necessary for successful ligament surgery when soft-tissue grafts are used for CrCL reconstruction (GREIS et al. 2001). Early weight bearing, which in dogs is often unavoidable, leads to graft necrosis and ultimately failure. Finally the visibility of the femoral attachment of the CrCL during arthrotomy is limited (WEISS 1991a).

The aforementioned issues concerning the most widely used operative techniques (LFTS, TPLO, TTA) might indicate that the “perfect surgical method” still does not exist. Intra-articular CrCL reconstruction can be performed minimally invasive under arthroscopic control (WINKELS et al. 2010b), reducing significantly patient morbidity. An anatomical approach, where the attachment points of the graft are located within the center of the insertion of the native ligament on the tibia and femur is at least in theory superior to other methods because it mimics the original anatomy of the joint. The good clinical outcomes and the reported absence of osteoarthritis progression (SPINDLER et al. 2011, HOFFELNER et al. 2012) of the anatomic ACL reconstruction in humans does not ensure that the method will be successful in dogs, but at least supports our belief that the intra-articular CrCL in dogs deserves a second chance.

The attachment points of the in the grafts during intra-articular have not been yet placed anatomically (see Fig. 1). While for the tibia the drilling of a bone tunnel, visually inside the footprint of the ligament, is a common practice (BENNETT and MAY 1991, LOPEZ et al. 2003), the preferential femoral attachment point remains the ‘over-the-top’ position, as first described in 1979 by Arnosczky et al. (ARNOCZKY 1979, HULSE et al. 1983, PATTERSON et al. 1991, BRUNNBERG et al. 1992, LOPEZ et al. 2003). Interestingly in a study where bone tunnel and the ‘over-the-top’ fixation were compared, in 91,3% of the cases with a femoral tunnel rupture of the prosthesis was observed (MONTGOMERY et al. 1988). Other older studies claim that the clinical outcome when bone tunnels were used is worse and could also explain why the ‘over-the-top’ fixation is preferred (BENNETT and MAY 1991, STEAD et al. 1991).

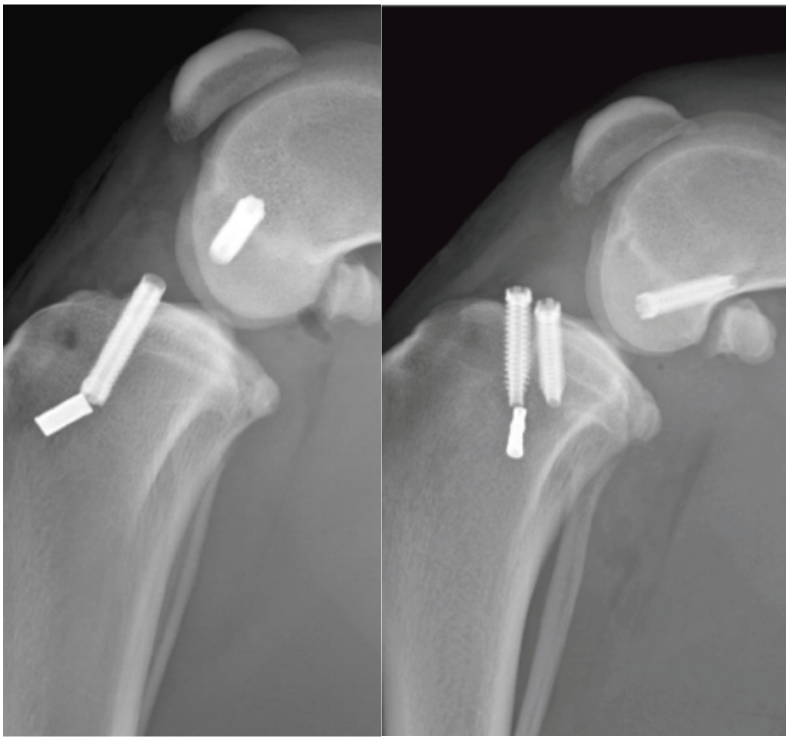

Figure 1. Not anatomically placed femoral tunnels in clinical patients. The implants are located too far cranial. (Courtesy of Dr. Randy Acker, KYON, Zurich).

Although the ‘over-the-top’ location is near the femoral attachment of the ligament, it is still not anatomical. Moreover, while for the tibia aiming devices have been used to aid drilling (LOPEZ et al. 2003, WINKELS et al. 2010b, TOBIAS and JOHNSTON 2011), there are no aiming devices available for the femur. Winkels et al. intensively investigated the tibial insertion of the CrCL. According to their studies the radiological location of the tibial attachment of the CrCL was defined (WINKELS et al. 2010a), and an aiming device to assist minimally invasive anatomical tibial tunnel drilling has been developed

(WINKELS et al. 2010b). The results were very promising as the adjustable aiming device achieved high precision in six cadaveric stifles.

In order to complete the surgical method and provide the basis of the anatomic intra-articular cruciate reconstruction in dogs, the overall aim of this study was to develop an aiming device for anatomical femoral tunnel drilling. In particular:

1. The first objective of this cadaveric study was to define the radiographic location of the center of the femoral attachment of the CrCL in middle to large breed dogs, for preoperative planning as well as intra- and post-operative control of anatomical placement of the intra-articular femoral tunnel opening.

2. Second objective of the study was to develop and validate an adjustable aiming device that allows for arthroscopic femoral tunnel placement, with similar accuracy to the tibia as described by Winkels et al. (WINKELS et al. 2010b).

2 Publications

2.1 Radiographic location of the femoral footprint of the cranial cruciate ligament in dogs

Bolia A, Winkels P, Bottcher P. Tierärztl Prax 2015; 45 (1) 23-30

ABSTRACT

Objective: To describe the radiographic location of the center of the femoral footprint of the cranial cruciate ligament (CrCL) in dogs.

Material and Methods: Using femora from 49 adult, orthopedically sound dogs (BW ≥ 20 kg), a radiopaque marker was placed on the cranial border of the femoral footprint of the CrCL. Computed tomography and 3D reconstruction of each femur was performed subsequently, followed by manual segmentation of the footprint on the 3D models and calculation of its center. Finally, virtual digital radiographs in two planes were produced and the location of the calculated center of the CrCL was expressed using three different methods (4x4 box grid method and percentage position for the medio-lateral projection; o'clock position for the disto-proximal projection).

Results: In the medio-lateral radiographs the center of the femoral footprint was consistently located in the second rectangle from the top of the most caudal column of the 4x4 grid. The mean percentage caudo-cranial and proximo-distal location was 20.2% (± 2.2) and 33.8% (± 3.7), respectively. In the disto-proximal radiograph, the o'clock position of the CrCL center was between 2 and 3 o'clock in 97.6%. **Conclusion(s):** The radiographic location of the center of the femoral footprint can be consistently predicted in medio-lateral and disto-proximal stifle radiographs of dogs over 20 kg.

Clinical Significance: The reported data can be used to plan and verify the placement of the femoral tunnel opening for intra-articular anatomic CrCL repair.

ZUSAMMENFASSUNG

Ziel: Bestimmung der radiologischen Lage des Zentrums des femoralen vorderen Kreuzbandursprungs beim Hund.

Material und Methoden: Die kraniale Begrenzung des femoralen Ursprungs des vorderen Kreuzbandes (VK) wurde mit einem röntgendichten Draht bei 49 Femora orthopädisch gesunder Hunde (KM > 20 kg) markiert. Anschließend wurde eine Computertomographie und 3D-Rekonstruktion jedes Femurs angerfertig, anhand derer der Ursprung manuell segmentiert und das Zentrum berechnet wurde. Schließlich wurden, basierend auf den 3D-Modellen, virtuelle Röntgenbilder in zwei Ebenen berechnet. An diesen wurde die Position des berechneten Zentrums mit drei unterschiedlichen Methoden bestimmt (4x4-Gitterbox-Methode und prozentuale Position für die medio-laterale Projektion; Ziffernblattmethode für die disto-proximale Projektion).

Ergebnisse: In der medio-lateralen Projektion befand sich das Zentrum des femoralen Kreuzbandursprungs im zweiten Rechteck von proximal in der kaudalen Spalte. Die mittlere prozentuale kaudo-kraniale und proximo-distale Position war 20,2 % (± 2,2), beziehungsweise 33,8% (± 3,7). Im disto-proximalen Röntgenbild lag in 97,6 % der Femora das Zentrum des femoralen Kreuzbandursprungs zwischen 14:00 und 15:00 Uhr.

Schlussfolgerung: Die radiologische Lage des vorderen Kreuzbandursprungs kann in medio-lateralen und disto-proximalen Röntgenbildern von Hunden mit einer KM > 20 kg vorhergesagt werden.

Klinische Relevanz: Die erarbeiteten Referenzwerte können für die Planung sowie die intra- und postoperative Kontrolle der femoralen Bohrkanalplatzierung bei der intraartikulären anatomischen VK-Rekonstruktion verwendet werden.

INTRODUCTION

Cranial cruciate ligament (CrCL) pathology is the most frequent cause of lameness in middle to large breed dogs (17). Degeneration of the CrCL leads to either partial or complete rupture of the CrCL with subsequent stifle instability, osteoarthritis and, in 52-70 % of the cases damage to the caudal horn of the medial meniscus (6, 29, 36). Many operative techniques addressing joint instability have been developed, and these include intra-articular CrCL reconstruction such as the "over-the-top" procedure (2), extra-articular procedures such as lateral suture stabilization (31) or tibial osteotomies with tibial plateau leveling osteotomy (TPLO), and tibial tuberosity advancement (TTA) being the most widely used examples (9, 34).

"Intra-articular repair of CrCL injuries is the gold standard for treatment in the human patient, but it has not met with enduring success in the canine patient" (22). Currently single as well as double-bundle reconstructions are performed in humans (19). The latter aims at replicating the anatomy of the CrCL more closely, taking into account the distinct cranio-medial and caudo-lateral bundles. In 1952, Paatsama reported the use of fascia lata as an intra-articular replacement for the CrCL in dogs, passing the graft through bone tunnels in the tibia and femur (25). Later, Arnozcky proposed the over-the-top method, passing a fascia lata graft through the joint without the use of bone tunnels (2), which facilitated the surgical technique. In a clinical study comparing the technique to extra-articular stabilization and TPLO, the intra-articular technique resulted in inferior limb function (8). Especially premature failure of the graft (39) has been reported and led to the wide use of the extra-articular procedures (22). Tibial osteotomies, especially TPLO, have become popular as they give superior functional results on long term, when compared to extra-articular suture stabilization (14, 23). However, for TPLO and TTA *in vivo* femoral subluxation has been reported in 33% and 70% respectively (20, 33) and late meniscal damage in 5.6% and 27.8% respectively (7, 18). These findings reflect the inability of both surgical methods to provide joint stability in every operated joint. Static joint stability provided by anatomical reconstruction of the CrCL should reduce the incidence of such complications (7) while at the same time providing near normal joint kinematics (16).

For a successful anatomical intra-articular repair procedure to be available in dogs, the following three prerequisites will have to be met (40): 1) a graft, either biological or synthetic, of similar strength to the native undegenerated CrCL which does not break or stretch under cycling loading throughout a whole canine lifespan; 2) secure fixation of the graft at the femur and tibia, preventing slippage of the graft and concomitant instability, and 3) anatomical placement of the graft at the center of the femoral and tibial attachment of the native CrCL in order to achieve near normal cranio-caudal as well as rotational stifle stability. In addition graft placement should be isometricall, resulting in even graft length during range of motion, assuring even tension within the graft (28). This can been achieved by finding two points, one at the femur and one at the tibia that do not change their distance throughout the range of stifle motion (26). Another approach relies on the true anatomy and therefore isometry of the graft similar to the native CrCL, using tunnels as closely as possible to the anatomic position of the CrCL insertions (1). The latter approach was chosen for the current study

Anatomical single-bundle CrCL reconstruction aims for restoration of the global biomechanical function of the native CrCL, and therefore tunnel positioning is performed to replicate the so-called “mid-bundle” of the native ligament, at the center of the respective footprints (1, 19). We do not consider replication of the functional heterogeneity of the native CrCL to be mandatory at this stage, as double-bundle reconstruction of the anterior cruciate ligament has failed to provide superior clinical results than single-bundle reconstruction in men (19). Accurate tunnel placement has been shown to be crucial in obtaining a successful outcome after anterior cruciate ligament reconstruction in humans (24), with misplacement of either of the tunnels occurring in up to 50 % of cases (4, 38), representing the overall most common cause for graft failure (24). The term tunnel misplacement refers to a state where the opening of the tunnel for intra-articular cruciate ligament reconstruction is not located at the requested position, which is centrally or near centrally in the footprint (37). We anticipate even higher rates of tunnel misplacement in dogs, because the canine stifle is only half to one third of the size of a human knee, and up to now, freehand tunnel drilling is commonly performed in dogs. Another difficulty that veterinarians have to overcome, and probably another important factor that overall contributes to the failure of the intra-articular cruciate repair in dogs, is the lack of postoperative compliance in dogs. Human patients always attend a controlled rehabilitation regimen, have to use crutches to reduce loading of the limb postoperative and wear a brace, which restricts joint flexion as well as graft overloading for several weeks to months flowing surgery (3, 21).

The aim of this cadaveric study is to define the radiographic location of the center of the femoral attachment of the CrCL in middle to large breed dogs, for preoperative planning as well as intra- and post-operative control of anatomical placement of the intra-articular femoral tunnel opening.

MATERIALS AND METHODS

Specimens

The left or right pelvic limbs from 49 adult, orthopedically sound dogs (BW ≥ 20 kg; mean 36.1 kg, range 20.3 - 57.0) were chosen randomly by flipping a coin and harvested via coxofemoral disarticulation. The dogs were euthanized for reasons unrelated to the study. The term ‘orthopedically sound’ was used when no pathologic findings (crepitus, instability) were present on post mortem palpation of the stifle and when the radiological examination of the stifles revealed neither osteoarthritic changes nor any “fat pad sign”. The limbs were either directly processed or sealed in plastic bags and stored at -18°C and then thawed at room temperature 24 hours before processing.

3D Modeling

Each femur was disarticulated at the stifle and all soft tissues, except for the attachment of the CrCL on the medial aspect of the lateral condyle, were removed. Afterwards, an orthopedic wire (∅ 0.4 mm) was glued (UHU® superglue, UHU, Germany) along the cranial border of the CrCL stump. Finally, transverse computed tomography (CT) of the distal half of each femur was performed using a multi-slice helical CT scanner (Phillips Brilliance, Phillips, Netherlands) with an average in-plane resolution of 0.17 mm (SD = 0.03 mm) and a slice thickness of 1 mm with an overlapping increment of 0.5 mm. Image reconstruction was done using a sharp bone filter (Filter type and Convolution Kernel D; Phillips Brilliance, Phillips, Netherlands). Three-dimensional (3D) surface reconstructions of the distal femur were calculated using dedicated image analysis software based on the VTK (VTK 3.0, Kitware Inc., New York, NY, USA, www.vtk.org) (see fig. 1A).

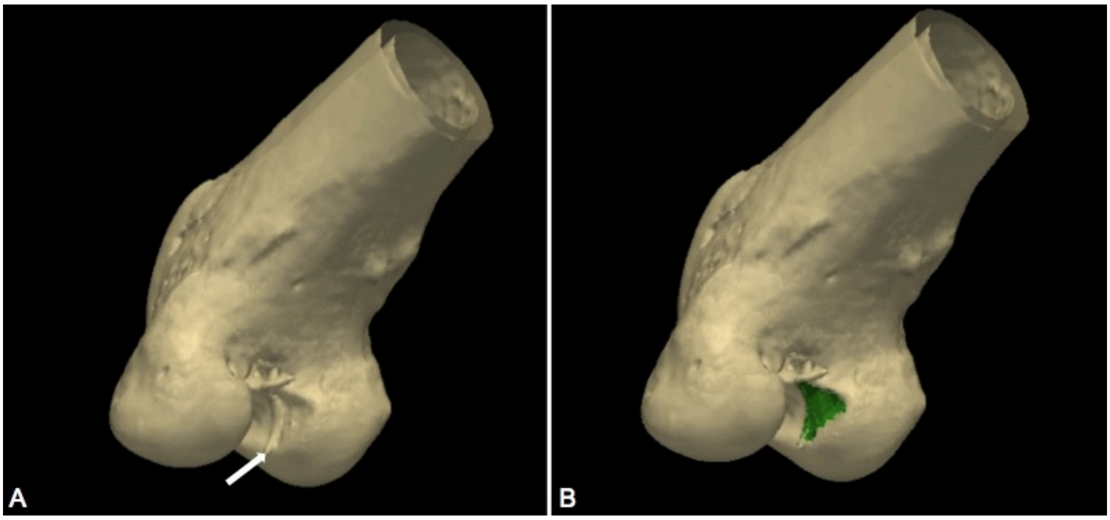

Figure 1. 3D reconstruction of the distal femur. A) An orthopedic wire (arrow) is marking the cranial border of the cranial cruciate ligament (CrCL) footprint. B) The footprint of the CrCL has been manually segmented on the 3D-model and marked in green.

Abbildung 1. 3D Rekonstruktion des distalen Femurs. A) Ein röntgendichter Draht (Pfeil) markiert die kraniale Grenze des vorderen Kreuzbandursprungs. B) Die Ursprungsfläche des vorderen Kreuzbandes wurde am 3D Model segmentiert und grün markiert.

Estimation of the Center of the CrCL Footprint

Because the triangle forming the CrCL footprint is not a planar surface, calculation of its center cannot be performed using 2D images. Therefore, the

CrCL footprint was manually segmented on the 3D models of the femora using special software based on the VTK (see fig. 1B). The following landmarks were used during segmentation: the cranial border was defined by the wire (see arrow in fig. 1), the condylar articular margin defining the distal margin and the caudal wall of the femur defining proximal border. The CrCL footprint is composed of two triangles, roughly orthogonal to each other, one lateral at the axial aspect of the lateral condyle and one proximal at the roof of the intercondylar fossa. The line connecting the two triangles divides the CrCL footprint in two equal portions (see Figure 2A), representing the median of the CrCL footprint. To verify this, the surface of the CrCL footprint was divided along the connecting line using ParaView (ParaView 3.0, Kitware Inc., New York, NY, USA; www.paraview.org). The area of the two resulting triangles was calculated using another software (3DSlicer 4.0, www.slicer.org) for the first 26 femora and expressed as a percentage of the total area of the femoral footprint. The center of the CrCL was defined to be located at the middle of the connecting line (see fig. 2B), referring to the concept of so called “mid-bundle” of the native ligament, when attempting single-bundle reconstruction. Using basic trigonometry, the midpoint of the connecting line was calculated in 3D space and a sphere (∅ 0.5mm) was placed at these coordinates on the 3D bone model in virtual space, marking the center of the CrCL footprint at the medial border of the lateral femoral condyle. For the remaining 23 femora the center was calculated based on the connecting line, without calculation of the two areas.

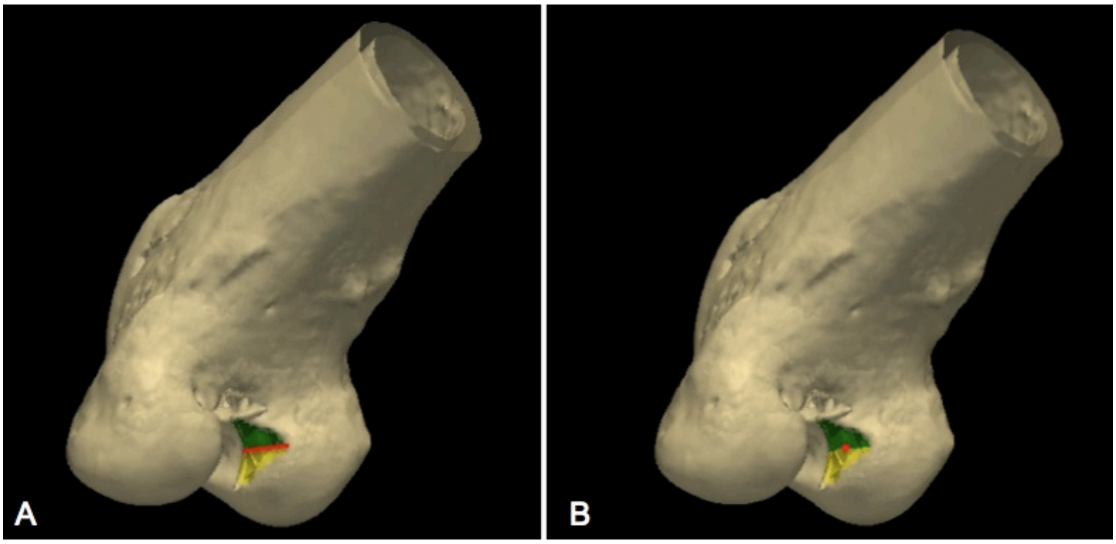

Figure 2. Determination of the center of the cranial cruciate ligament (CrCL) footprint. A) The CrCL footprint is composed of two equal triangles (green, yellow). B) The midpoint of the line connecting both triangles is defined as the center of the CrCL footprint.

Abbildung 2. Bestimmung der Lage des Zentrums des vorderen Kreuzbandursprungs. A) Der vordere Kreuzbandursprung besteht aus zwei gleich großen Dreiecken (grün, gelb). B) Der Mittelpunkt der Verbindungslinie beider Dreiecke ist das Zentrum des vorderen Kreuzbandursprungs.

Radiographic Measurements

Within ParaView, virtual digital radiographs of each femur were calculated using volume ray casting. Plain medio-lateral radiographs were produced (see fig. 3A), and the sphere marking the center of the femoral footprint of the CrCL projected into the virtual x-ray (see fig. 3B).

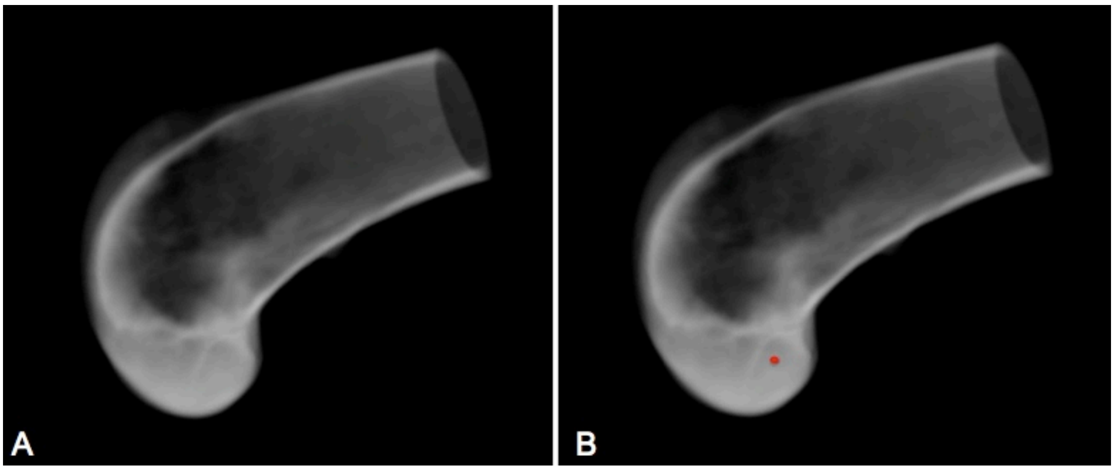

Figure 3. Medio-lateral virtual digital radiograph of the distal femur. A) Plain radiograph: Note the condensed linear shadow along the roof of the intercondylar fossa, called Blumensaat's

line. B) The sphere, which was placed at the center of the CrCL footprint using the methodology depicted in fig. 1 and 2 has been projected into the digital radiograph.

Abbildung 3. Virtuelles Röntgenbild des distalen Femurs im medio-lateralen Strahlengang. A) Natives Röntgenbild: Die röntgendichte Linie am Dach der Fossa intercondylaris wird als Blumensaatlinie bezeichnet. B) Die in Abb. 1 und 2 am Zentrum des vorderen Kreuzbandursprungs platzierte Kugel wird in das virtuelle Röntgenbild projiziert.

Based on these virtual x-ray images the relative position of the CrCL center (center of the sphere) was defined using the 4 x 4 box grid method (see fig. 4A) (5). The most proximal line of the grid is drawn overlapping and parallel to the Blumensaat's line, by manually fitting a line to the slightly irregular Blumensaat's line. The Blumensaat's line is a condensed linear shadow on the lateral radiographic projection of the stifle that marks the roof of the intercondylar notch. The cranial and caudal lines of the box are tangent to the most cranial and caudal aspects of the femoral condyles. The distal border of the box is defined by the most distal aspect of the femoral condyles. Then, the rectangular of the grid, in which the CrCL center (center of the sphere) was located, was marked. Finally, the location of the center was also calculated in relation to the uppermost and most caudal corner of the grid, expressed as percentage of the total length and height of the 4x4 grid box (see fig. 4B).

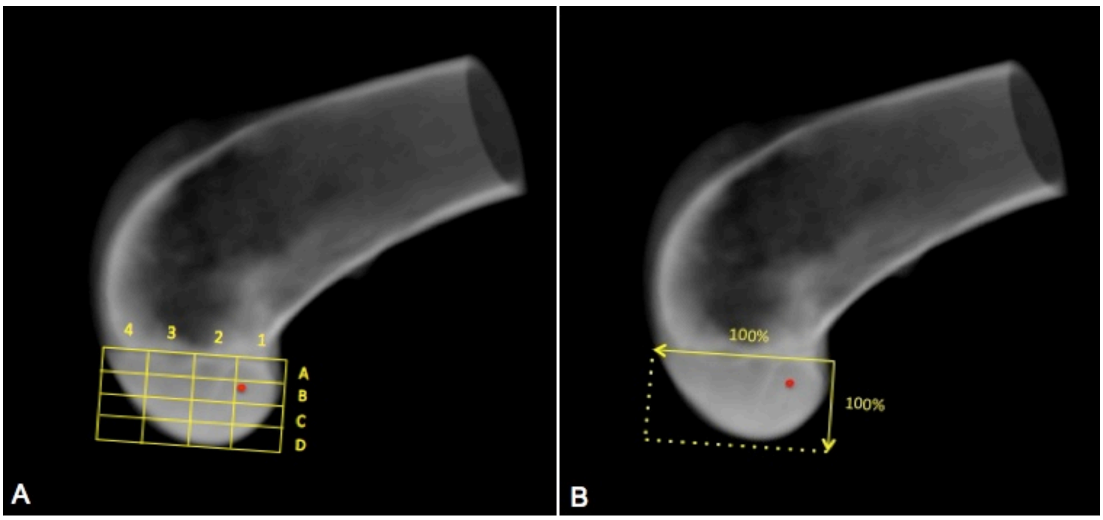

Figure 4. Determination of the relative location of the center of the cranial cruciate ligament (CrCL) in the sagittal plane. A) 4x4 box grid method: The most proximal line of the grid is drawn overlapping and parallel to the Blumensaat's line. The cranial and caudal lines of the box are tangent to the most cranial and caudal aspects of the femoral condyles. The distal

border of the box is defined by the most distal aspect of the femoral condyles. B) Caudo-cranial and proximo-distal position in relation to the uppermost and most caudal corner of the grid, expressed as percentage of the total length and height of the 4x4 grid box.

Abbildung 4. Bestimmung der relativen Position des Zentrums des vorderen Kreuzbandursprungs im medio-lateralen Strahlengang. A) 4x4-Gitterbox-Methode: Die proximale Linie der Box verläuft entlang der Blumensaatlinie. Die kraniale und kaudale Linien sind Tangenten zur kranialen und kaudalen Begrenzung der Femurkondylen. Die distale Linie der Box liegt auf der distalen Grenze der Femurkondylen. B) Prozentuale kaudo-kraniale und proximo-distale Position in Bezug auf die proximo-kaudale Ecke der Box.

The position of the CrCL center on the transverse plane was estimated based on virtual disto-proximal radiographs, along the long axis of the femur (see fig. 5A), based on the o'clock method (13). A circle was fitted to the axial border of the medial condyle and the most proximal aspect of the intercondylar fossa. A line passing through the center of the circle, parallel to the tangent of the distal aspect of both femoral condyles, representing the 9 to 3 o'clock axis of a virtual clock face, was drawn (see fig. 5C). The position of the CrCL center was then expressed in respect to this clock face. Measurements of right stifles were converted to left stifles.

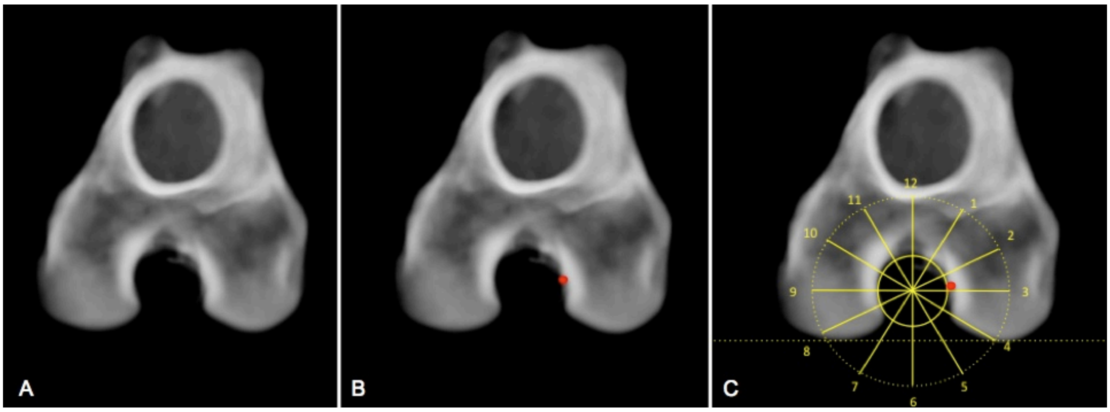

Figure 5. Disto-proximal virtual digital radiograph of the distal femur. A) Plain radiograph. B) The center of the CrCL footprint is marked with a red sphere. C) Determination of the location of the center using the o'clock method. A circle was fitted to the axial border of the medial condyle and the most proximal aspect of the intercondylar fossa. A line passing through the center of the circle, parallel to the tangent of the distal aspect of both femoral condyles, representing the 9 to 3 o'clock axis of a virtual clock face, was drawn. The position of the CrCL center (the red sphere) was then expressed in respect to this clock face. Measurements of right stifles were converted to left stifles.

Abbildung 5. Disto-proximales virtuelles Röntgenbild des distalen Femurs. A) Natives Röntgenbild. B) Das Zentrum des vorderen Kreuzbandursprungs ist mit einer roten Kugel markiert. C) Bestimmung der Lage des Zentrums des vorderen Kreuzbandursprungs mit der Ziffernblattmethode. Es wurde ein Kreis bestimmt, welcher die axiale Kante der medialen Femurkondyle und das proximale Dach der Fossa intercondylaris tangiert. Zusätzlich wurde eine, durch das Zentrum des Kreises verlaufende Linie, parallel zur Tangente der distalen Begrenzung der Femurkondylen eingezeichnet. Diese Line stellt die Neun zu Drei Uhr Achse des Ziffernblatts dar. Die Lage des Zentrums des vorderen Kreuzbandursprungs (rote Kugel) wurde in Bezug zum Ziffernblatt ausgedrückt. Messungen für rechte Kniegelenke wurden entsprechend gespiegelt.

Statistical Analysis

Continuous data was expressed as mean and standard deviation because D'Agostino-Pearson testing attested normal distribution of data. An analysis as to whether the CrCL footprint is divided into two equal triangles by the connecting line used to define the CrCL center was performed using a paired T-test with $P \leq 0.05$. Commercial software (MedCalc v10.4.8.0, MedCalc Software, Ostend, Belgium) was used for all calculations.

RESULTS

The most common breed was mixed breed, followed by Golden Retriever, Labrador Retriever and Rottweiler. The area percentages of the two triangles composing the CrCl footprint were not statistically different ($n = 25$, $p = 0.497$). The mean area percentage of the proximal area was 49.7 % (± 2.5), while the lateral was 50.3% (± 2.5), proving that the line used to defined the center of the CrCL footprint was the median.

Medio-Lateral Radiograph

According to the 4 x 4 box grid method, the center was consistently located in the B1 rectangle, which represents the second rectangle from the top of the most caudal column (see fig. 6). The percentage mean caudo-cranial and proximo-distal locations were 20.2 % (± 2.2) and 33.8% (± 3.7), respectively (see fig. 7).

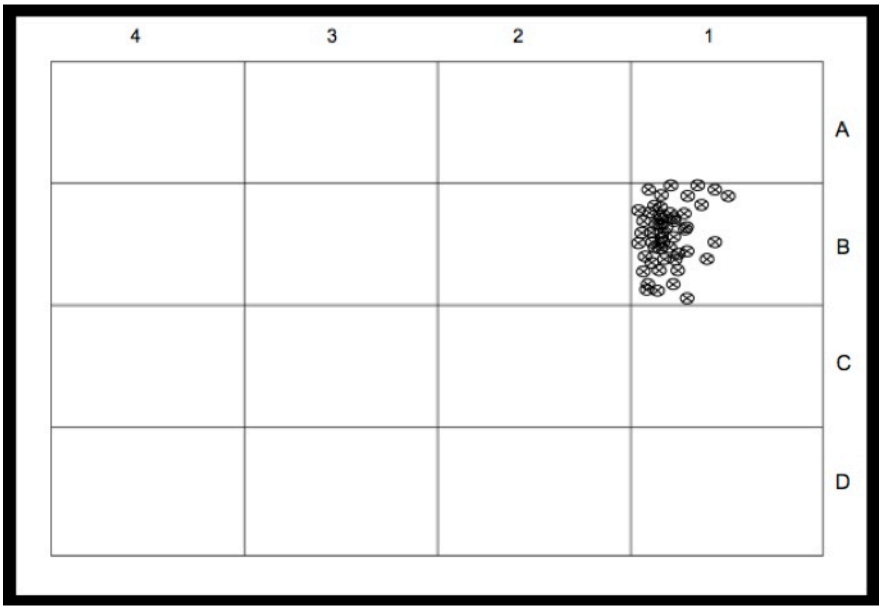

Figure 6. Relative location of the center of the cranial cruciate ligament footprint in the medio-lateral projection according to the 4x4 box grid method (n = 49). In every case the center of the CrCL footprint is located in the B1 rectangle, the second rectangle from the top of the most caudal column.

Abbildung 6. Relative Position des Zentrums des vorderen Kreuzbandursprungs im medio-lateralen Strahlengang anhand der 4x4-Gitterbox-Methode (n = 49). Bei allen Kniegelenken befand sich das Zentrum des vorderen Kreuzbandursprungs im Rechteck B1, das zweite Rechteck von proximal in der kaudalen Spalte.

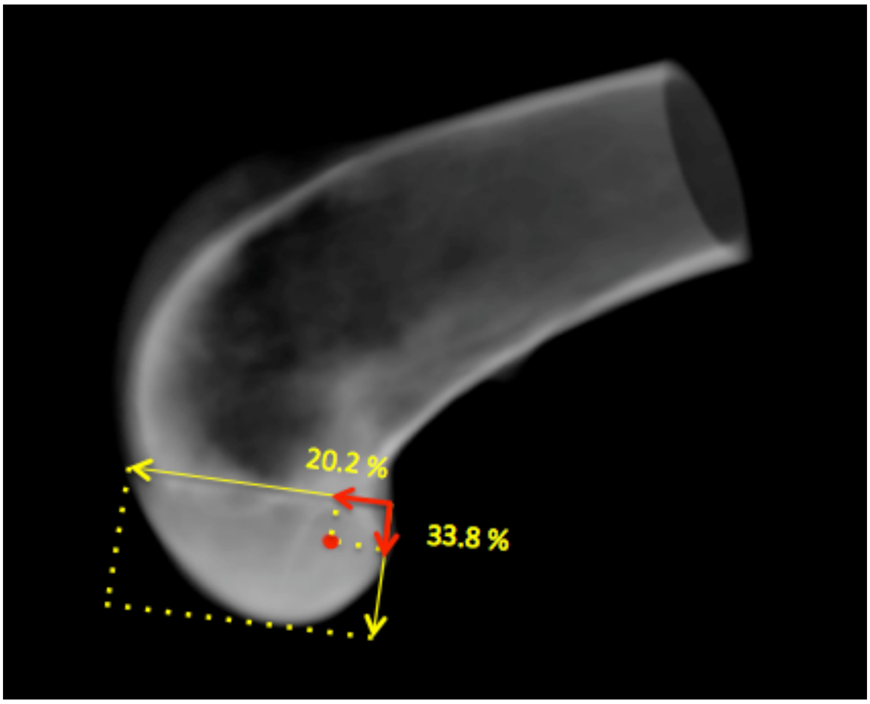

Figure 7. The percentage mean caudo-cranial and proximo-distal locations of the center of the femoral CrCl footprint were 20.2 % (± 2.2) and 33.8% (± 3.7), respectively (n = 49).

Abbildung 7. Die Prozentuale mittlere kaudo-kraniale und proximo-distale Position des Zentrums der vorderen Kreuzbandursprungs waren 20,2 % (± 2,2) beziehungsweise 33,8% (± 3,7) (n = 49).

Proximo-Distal Radiograph

The o'clock position of the CrCL center was between 2 and 3 o'clock in 97.6% (39/49) of the femora and exactly 3 o'clock in the remaining 2.4 % (10/49) (see fig. 8).

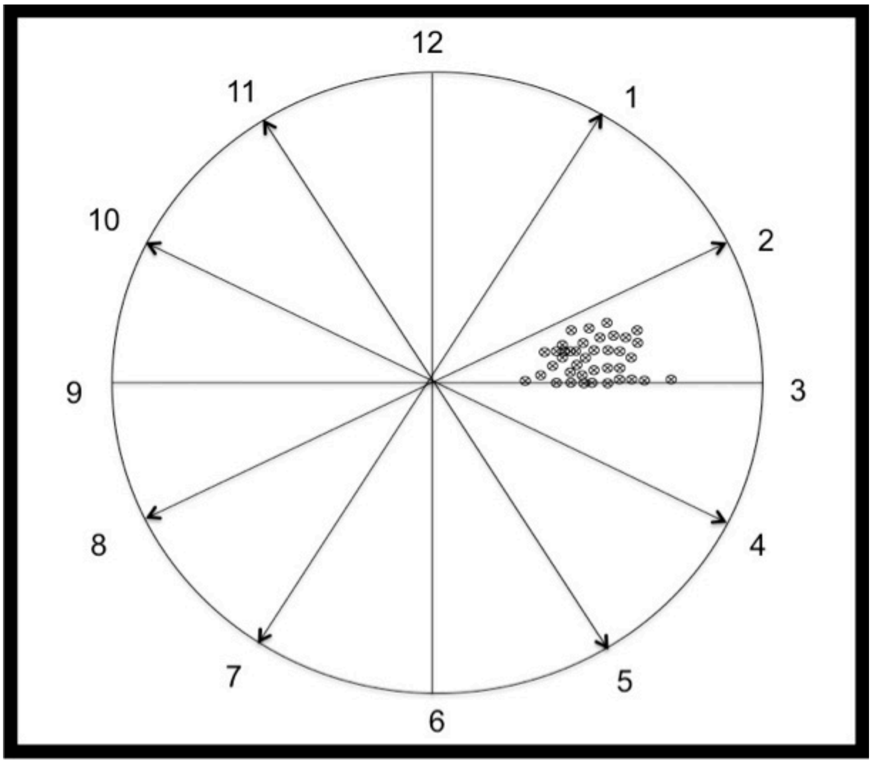

Figure 8. Location of the center of the cranial cruciate ligament footprint in the disto-proximal projection using the o'clock method (left side, n = 49; results for right femora have been mirrored). The center is located between 2 and 3 o'clock in 97.3 % of the stifles and at exactly 3 o'clock for the remaining. For right femora the position is between 9 - 10 o'clock and at 9 o'clock, accordingly.

Abbildung 8. Bestimmung der Lage des Zentrums des vorderen Kreuzbandursprungs in der disto-proximalen Projektion anhand der Ziffernblattmethode (Linke Seite, n = 49; Ergebnisse für rechte Kniegelenke wurde gespiegelt). Das Zentrum lag in 97,6 % der Fälle zwischen zwei und drei Uhr bzw. genau auf drei Uhr bei den Übrigen. Für rechte Femora liegt die Position zwischen nein und zehn bzw. genau bei neun Uhr.

DISCUSSION

Intra-articular misplacement of either the tibial or femoral bone tunnel opening accounts for 70-80 % of all documented technical errors in people undergoing revision for graft failure after intra-articular anterior cruciate ligament repair (12, 38, 42, 43). Misplacement of the graft may cause either restricted flexion of the knee, if the graft resists the increased loads, or it may lead to elongation of the graft and subsequent failure, both resulting in recurrent joint instability (1, 15). Therefore, accurate tunnel placement appears to be one of the most important technical aspects in intra-articular CrCL repair.

The reported data concerning the sagittal and transverse radiographic location of the center of the CrCL footprint can be used for preoperative planning or to verify intra- and postoperatively the placement of the femoral tunnel opening when attempting anatomic intra-articular CrCL repair. Our initial expectation to find an anatomical correlation between femoral morphometric characteristics (e.g. size of the femoral condyles or length of the Blumensaat's line) and the caudo-cranial and proximo-distal location of the center of the femoral CrCL footprint was not fulfilled when performing a pilot study (data not shown). As a consequence, we adopted the method widely used in human patients, expressing the location in a relative manner (5). If an absolute measurement in millimeters is needed, for example when using an aiming device, the relative position can be easily converted to an absolute measure once the radiograph has been appropriately calibrated.

As previously mentioned and in contrast to the results of a recently published study concerning the radiographic location of the origin of the CrCL for lateral suture stabilization (30), we found no correlation between the length of the Blumensaat's line and the cranio-caudal location of the center of the femoral footprint of the CrCL. The study of Reichert et al. uses a different methodology and this might explain the discrepancy between both studies. The center in our study is calculated based on the complex 3D anatomy of the footprint, while the measurements of Reichert et al. are based on an uniplanar projection of the footprint on the mediolateral radiograph. We used the Blumesaat's line just as a landmark for drawing the grid box. The width of the grid box however is defined by the most cranial and caudal border of the condyles and not by the length of the Blumensaat's line. The proximo-distal location on the other hand was measured using the same landmarks as in the study of Reichert et al., but their position seems to be different to what we found (46.6 % vs. 33.8% in the current study). This might be attributed to the fact that their sample size was relatively small (12 vs. 49 limbs in the current study) and that we did not use paired limbs, which probably contributed to a more heterogenic population in our study. Another significant difference between both studies is the different size of dogs studied, with the dogs in the current study belonging to a weight class of 20.3 – 57.0 kg compared to 12.9 - 26.2 kg.

We adopted the concept of anatomic single-bundle reconstruction, using the center of the CrCL as target for tunnel placement because this approach has become the current standard in human anterior cruciate ligament surgery (19). The fact that the canine footprint is divided into two equal parts, one at the roof of the intercondylar fossa and another at the axial aspect of the lateral condyle, may imply that a single-bundle technique may be inadequate in dogs. However, investigating whether a single- or double-bundle reconstruction should be performed in dogs is beyond the scope of the current study and even in men the double-bundle reconstruction failed to provide better clinical results (19, 35). Our proposition of placing the femoral drill hole in the central portion of the CrCL footprint mimics the anatomical approach, currently popular in human anterior cruciate ligament reconstruction, but the optimal graft placement for restoring normal (or close to normal) joint function under *in vivo* loading is unknown in dogs and further studies are required to elucidate on this point.

Both the grid-technique as well as the percentage measurements are easily done on a medio-lateral radiograph of the distal femur, which is part of the standard clinical work-up of any stifle case. Intraoperatively, fluoroscopy could be used to obtain the desired view. Even though the disto-proximal projection for the o'clock method is not part of the usual radiographic projections and may require some practice, femoral torsion is assed routinely this way (10). Therefore we consider the proposed pre- and potentially intra as well as postoperative radiographic measurement a realistic addition to existing intra-articular CrCL reconstruction techniques. Nevertheless, anatomical graft placement will only become a routine technique, if the translation of the radiographic measurements into an adjustable aiming device for femoral tunnel drilling will be achieved. An aiming device based on the proximal tibial length, measured on a medio-lateral stifle radiograph, has already been developed (41). Another potential limitation of the present study is that our specimens belong to dogs ≥ 20 kg and therefore the technique may not be reliable in smaller patients (30).

To conclude, the radiographic location of the center of the femoral footprint of the CrCL can be consistently predicted in medio-lateral and disto-proximal radiographs of the distal femur. In particular, on the sagittal plane the center of the CrCL footprint is located in the second rectangle from the top of the most caudal column according to the 4 x 4 box grid method. More precisely, its caudo-cranial and proximo-distal position is located about 20% and 35% away from the most caudal and proximal corner of the grid box. On the transverse plane, the center of the CrCL footprint is located between the 2 and 3 o'clock position for left femora and between the 9 and 10 o'clock position for right femora in 98% of the cases.

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2.2 Arthroscopic assisted femoral tunnel drilling for the intra-articular anatomic cranial cruciate ligament reconstruction in dogs

Bolia A, Bottcher P. Tierärztl Prax 2015; 43 (5) 299-308

ABSTRACT

Objective: To develop and test an arthroscopic aiming device for extra- to intra- articular femoral tunnel drilling emerging at the center of the femoral insertion of the cranial cruciate ligament (CrCL) in medium to large breed dogs. **Material and Methods**: Hindlimbs (n=12) of 6 cadaveric dogs (≥20 kg BW). One hindlimb from each cadaver was randomly chosen. On a standard medio-lateral stifle radiograph the caudo-cranial position of the CrCL center was measured and transferred onto an adjustable aiming device. After arthroscopic debridement of the CrCL the aiming device was hooked behind the lateral condyle and a 2.4 mm guide pin was placed from extra-to-intra-articular. The intra-articular position of the resulting bone tunnel was evaluated radiographically as well as compared to the anatomic CrCl center of the contralateral hindlimb using 3D renderings. **Results:** According to the postoperative radiographs all six drill tunnels were located at or near the CrCL center. The median absolute 3D error from the anatomical center of the CrCL was 0.6 mm (range: 0.2 – 0.9 mm). **Conclusion(s):** Precise anatomic placement of the femoral tunnel for intra-articular repair of the CrCL was achieved using an adjustable aiming device. **Clinical Significance:** The proposed technique will reduce femoral tunnel misplacement when performing intra-articular CrCL repair in dogs. In combination with the published technique for arthroscopic tibial tunnel drilling using a similar aiming device, the technical requirements for arthroscopic assisted tunnel positioning for anatomical graft replacement are available.

ZUSAMMENFASSUNG

Ziel: Entwicklung und Erprobung eines Zielgerätes für die arthroskopisch-assistierte, anatomische vordere Kreuzbandrekonstruktion beim Hund. **Material und Methoden:** Hintergliedmaßen (n = 12) von 6 Hundekadavern (KM ≥20 kg) wurden verwendet. Eine Gliedmaße jedes Kadavers wurde zufällig ausgewählt und die kaudo-kraniale Lage des Zentrums des vorderen Kreuzbandansatzes (vKBA) in medio-lateralen Röntgenbildern berechnet und anschließend auf ein justierbares Zielgerät übertragen. Nach arthroskopischer Resektion des vorderen Kreuzbandes wurde das Zielgerät hinter der lateralen Kondyle eingehakt und ein 2,4 mm starker Steinmann Pin von extra nach intraartikulär platziert. Die Position der resultierenden Bohrkanäle wurde sowohl röntgenologisch bestimmt als auch dreidimensional mit dem anatomischen Zentrum des vKBA der kontralateralen Hintergliedmaßen anhand dreidimensionaler Modelle verglichen. **Ergebnisse:** In allen postoperativen Röntgenaufnahmen lagen die sechs Bohrkanäle im bzw. nahe dem Zentrum des vKBA. Die 3D-Messungen ergaben eine mediane Abweichung der Bohrkanalposition im Vergleich zum anatomischen Zentrum der kontralateralen Seite von 0,6 mm (Bereich: 0,2 – 0,9 mm). **Schlussfolgerung:** Die präzise anatomische Platzierung des femoralen Bohrkanals für die intraartikuläre Rekonstruktion des vorderen Kreuzbandes ist bei Verwendung eines justierbaren Zielgerätes möglich. **Klinische Relevanz**: Die beschriebene Methode wird helfen Fehlplatzierung des femoralen Bohrkanals im Zuge der intraartikulären vorderen Kreuzbandplastik zu reduzieren. In Kombination mit dem bereits beschriebenen tibialen Zielgerät sind nun die technischen Voraussetzungen für die arthroskopisch assistierte anatomische vordere Kreuzbandplastik in der Tiermedizin gegeben.

INTRODUCTION

Pathology of the cranial cruciate ligament (CrCL) is the most frequent cause of hindlimb lameness in middle to large breed dogs (14). Degeneration of the CrCL leads to either partial or complete rupture of the CrCL with subsequent stifle instability, osteoarthritis and, in 52-70 % of the cases damage to the caudal horn of the medial meniscus (18). Over the years numerous operative techniques have been developed, and these include intra-articular CrCL reconstruction such as the "over-the-top" procedure (2), extra-articular procedures such as lateral suture stabilization, tightrope, fibular head transposition (28) or the so called dynamic stabilization procedures with tibial plateau leveling osteotomy (TPLO), and tibial tuberosity advancement (TTA) being the most widely used procedures (18).

In contrast to human medicine, where anatomic reconstruction of the anterior cruciate ligament (ACL) is considered the treatment of choice, intra-articular repair in dogs is not commonly performed and until now has not met with enduring success (19, 20). In the veterinary medicine as early as in 1952, Paatsama reported the use of fascia lata as an intra-articular replacement for the CrCL in dogs, passing the graft through bone tunnels in the tibia and femur (24). Later Arnozcky proposed the over-the-top method, passing a fascia lata graft through the joint without the use of bone tunnels (2), which facilitated the surgical technique. In a clinical study comparing this technique to extra-articular stabilization and TPLO, the intra-articular method resulted in inferior limb function (5). Especially premature failure of the graft (32) has been reported and led to the wide use of extra-articular procedures (20). Tibial osteotomies, especially TPLO, have become popular as they give superior functional results on long term, when compared to extra-articular suture stabilization (10, 22). However, for TPLO and TTA *in vivo* femoral subluxation has been reported in 33 % and 70 %, respectively (17, 27), and late meniscal damage in 5.6 % and 27.8 %, respectively (4, 15). These findings reflect the inability of both surgical methods to provide joint stability in every operated joint. Static joint stability provided by anatomical reconstruction of the CrCL should reduce the incidence of such complications (4) while at the same time providing near normal joint kinematics, as it has already been shown in the human medicine (13). However it is questionable if the anatomical cranial cruciate reconstruction in dogs can restore the stifle joint kinematics, as no in vivo studies have been published so far.

For a successful anatomic intra-articular repair procedure to be available in dogs, the following three prerequisites will have to be met (33): 1) a graft, either biological or synthetic, of similar strength to the native undegenerated CrCL which does not break or stretch under cycling loading throughout a whole canine lifespan; 2) secure fixation of the graft at the femur and tibia, preventing slippage of the graft and concomitant instability, and 3) anatomical placement of the graft at the center of the femoral and tibial attachment of the native CrCL in order to achieve near normal cranio-caudal as well as rotational stifle stability. This approach relies on the true anatomy and therefore isometry of the graft similar to the native CrCL (1). Anatomic reconstruction can be defined as the functional restoration of the CrCL to its native dimensions, collagen orientation, and insertion sites (26). This type of reconstruction suggests that the tunnels have to be placed at the center of the native femoral and tibial insertion sites (31). This approach, which was first described in human ACL reconstruction, was chosen in the current study because it has been shown that anatomic ACL reconstruction provides better anterior translational as well as rotational stability than purely isometric techniques (36).

Accurate tunnel placement has been shown to be crucial in obtaining a successful outcome after anterior cruciate ligament reconstruction in humans, representing the overall most common cause for graft failure (23). The term tunnel misplacement refers to a state where the opening of the tunnel for intra-articular cruciate ligament reconstruction is not located at the requested position, which is centrally or near centrally in the footprint (30). We anticipate even higher rates of tunnel misplacement in dogs, because the canine stifle is only half to one third of the size of a human knee, and up to now, freehand tunnel drilling is commonly performed in dogs. Another difficulty that veterinarians have to overcome, and probably another important factor that overall contributes to the failure of the intra-articular CrCL repair in dogs, is the lack of postoperative compliance in dogs. Human patients always attend a controlled rehabilitation regimen, have to use crutches to reduce loading of the limb postoperative and wear a brace, which restricts joint flexion as well as graft overloading for several weeks to months following surgery (11).

In 2010 Winkels et al. reported that the radiographic location of the center of the tibial CrCL insertion can be individually determined on standard stifle radiographs (34). This led to the development of an adjustable aiming device for anatomic tibial tunnel drilling in dogs (33). Evaluation of the technique in six cadaveric stifles showed that arthroscopic outside-to-inside tunnel drilling achieved high precision (maximal error of 1 mm).

To the knowledge of the authors there are no adjustable aiming devices for anatomic femoral tunnel drilling in dogs currently available. However, the exact radiological location of the individual femoral CrCL attachment has recently been described (3). Aim of the present study was to develop and validate an adjustable aiming device for arthroscopic femoral tunnel placement, similar to the tibia as described by Winkels et al. (33). The working hypothesis was that arthroscopic tunnel placement emerging at the center of the femoral footprint of the CrCl would be possible with the same precision (≤1 mm) as reported for the tibia.

MATERIALS AND METHODS

Specimens

Both the right and left hindlimb of 6 orthopedically sound mature dog cadavers (n=12) weighing ≥20 kg were harvested via coxo-femoral disarticulation. The six cadavers used consisted of two mixed breed dogs, a Rhodesian ridgeback, a German shepherd, a Doberman and a Labrador retriever. The mean weight was 31.3 kg (range: 23 to 42 kg). The dogs were euthanized for reasons unrelated to the study. The term ‘orthopedically sound’ was used when no pathologic findings (crepitus, instability) were present on post mortem palpation of the stifle and when the radiological examination of the stifles revealed neither osteoarthritic changes nor any “fat pad sign”. The limbs were either directly processed or sealed in plastic bags and stored at -18°C and then thawed at room temperature 24 hours before processing.

Femoral Tunnel Drilling

Femoral Aiming Device

The aiming device consists of a drill sleeve (∅ 2.4mm), a hook and a handle connecting these two components (KYON, Switzerland) at a 90° angle (Fig. 1). The hook can be moved along its central axis, allowing for adjustment of the caudo-cranial offset of the resulting drill tunnel. Both the aiming rod and the sleeve are disconnectable, which allows placement of an aiming pin and subsequent disassembling of the handle and the hook in-situ.

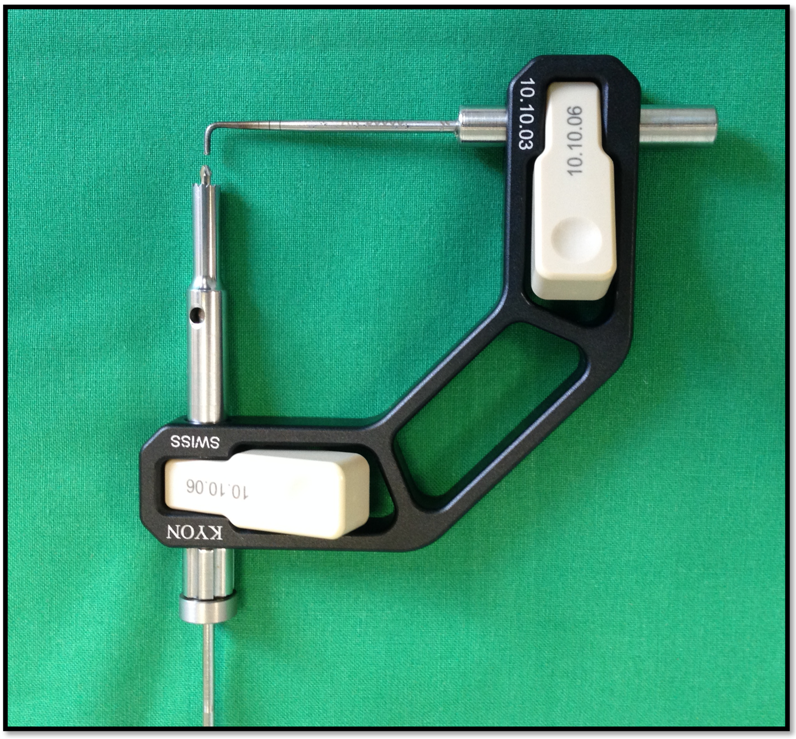

Figure 1. The aiming device (modified KYON aiming device, KYON, Switzerland) consists of a drill sleeve (∅ 2.4 mm), a hook and a handle connecting these two components at 90°. The hook can be moved along its central axis, allowing for adjustment of the caudo-cranial offset of the resulting drill tunnel.

Abbildung 1. Das Zielgerät (modifiziertes KYON Zielgerät, KYON, Schweiz) besteht aus einer Bohrhülse (∅ 2,4 mm) und einem Haken die an einem Handstück 90° zueinander angebracht sind. Der Hacken kann entlang seiner Längsachse verschoben werden, wodurch die kaudo-kraniale Position des Bohrkanals eingestellt wird.

Arthroscopic assisted femoral tunnel drilling

One hindlimb from each cadaver was randomly chosen (n=6, 3 right and 3 left) and a standard medio-lateral stifle radiograph was taken, with a metallic sphere of 25 mm diameter at the same distance from the flat panel detector as the tibial tuberosity, to allow for image calibration later on. On that image the caudo-cranial position of the CrCL center (ccPosPre) was calculated being located 20.2% of the length of the superimposed femoral condyles along the Blumensaat line (3). Percentage values were finally converted to absolute value in millimeters using standard image calibration technique. ccPosPre was then transferred onto to the aiming device, by adjusting the offset of the hook according to the calculated distance using a caliper (Fig. 2).

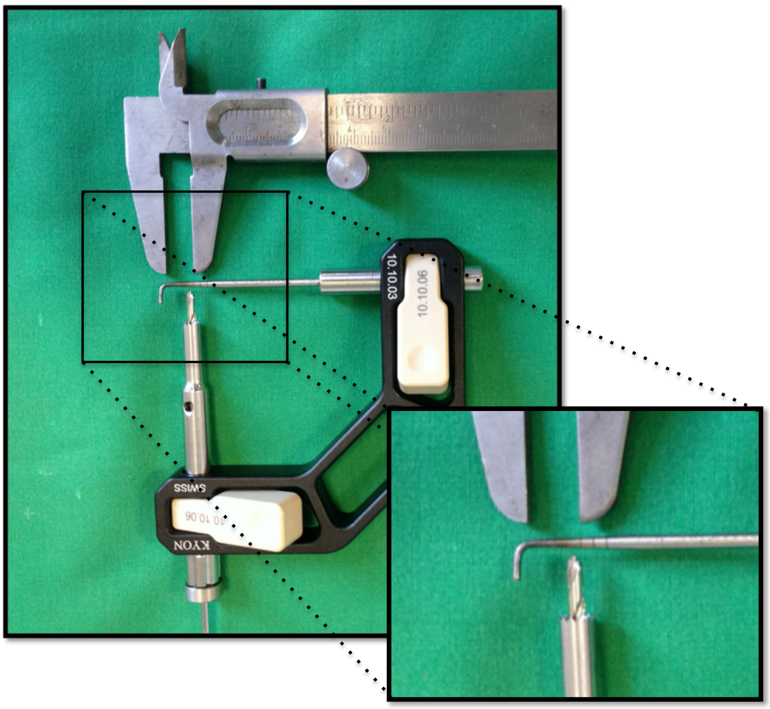

Figure 2. The radiologically determined caudo-cranial position of the center of the CrCL footprint (ccPosPre) is transferred onto to the aiming device, by adjusting the offset of the hook using a caliper.

Abbildung 2. Die radiologisch bestimmte kaudo-kraniale Position des Zentrums des Vordenkreuzbandansatzes (ccPosPre) wird mit Hilfe einer Schiebelehre auf das Zielgerät übertragen, indem der Haken entsprechend verschoben wird.

Standard stifle arthroscopy was performed by 1 investigator (A.B.) with assistance (P.B.), simulating dorsal recumbency, using a 2.4 mm 30° fore oblique arthroscope (Karl Storz GmbH & Co. KG, Tuttlingen, Germany) while the stifles were held at 90° flexion. Scope and working portal were located lateral and medial to the patellar ligament, respectively, midway between the distal pole of the patella and the tibial tuberosity. After partial debridement of the retropatellar fat pad using a motorized shaver (APS II Shaver, Arthrex, Naples, Florida, USA), the CrCL was transected using a retrograde knife (Dr. Fritz GmbH, Tuttlingen, Germany). Visualization of the femoral footprint of the CrCL was achieved by resection and thorough debridement of the CrCL using a combination of shaving and radio-frequency ablation (ArthroCare, ArthroCare Corporation, Austin, USA). Once the footprint was fully visible (Fig. 3A) the scope and working portal were interchanged and the hook of the calibrated aiming device inserted through the lateral portal. Under arthroscopic visualization the hook was anchored behind the lateral femoral condyle and pushed against the medial aspect of the lateral condyle (Fig. 3B). The inclination of the hook was defined by the anchor point at the caudal aspect of the lateral femoral condyle and contact of the hook's body on the roof of the intercondylar fossa, just alongside the origin of the caudal cruciate ligament.

After an 1.5 cm skin incision on the lateral side of the distal femur, and blunt dissection of the soft tissues until reaching the bone, the drill sleeve of the guide was firmly seated against the lateral femoral cortex, at an angle of approximately 45° to the horizontal plane, locking the guide into position. A guide pin (∅ 2.4 mm) with threaded tip was introduced and advanced under arthroscopic control. Drilling was stopped when the pin emerged at the medial aspect of the lateral femoral condyle. The tip of the pin was then aligned flush with the articular surface. The aiming device was finally detached and removed while the pin was left in place.

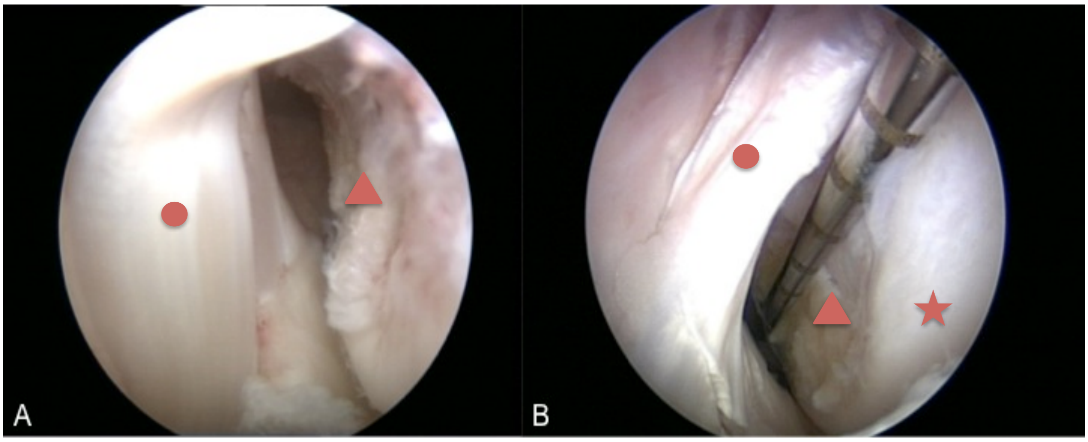

Figure 3. Arthroscopic images after debridement of the CrCL stump (left stifle, lateral to the left). After unobstructed visualization of the femoral footprint (A) the hook was anchored behind the lateral femoral condyle and pushed against the medial aspect of the lateral condyle (B). The origin of the caudal cruciate ligament was used as the cranial landmark for the disto-proximal orientation of the hook.

circle: caudal cruciate ligament, triangle: femoral footprint of the CrCL, star: lateral femoral condyle

Abbildung 3. Arthroskopische Bilder nach Resektion des vorderen Kreuzbandes (linkes Kniegelenk, lateral links im Bild). Nachdem vollständiger visueller Darstellung des Bandansatzes (A), wurde der Haken hinter der lateral Femurkondyle eingehakt und gegen die Innenseite der Kondyle gepresst (B). Der Ursprung des hinteren Kreuzbandes diente als kraniale Landmarke für die disto-proximale Orientierung des Hakens.

Kreis: hinteres Kreuzband; Dreieck: femoraler Ansatz des vorderen Kreuzbandes; Stern: laterale Femurkondyle

Evaluation of Achieved Tunnel Position

Radiographic assessment of achieved tunnel position

For each of the operated six stifles two-plane radiographs (medio-lateral and proximo-distal) were obtained (Fig. 4), while the guide pin was left in place in order to identify the exit point of the femoral tunnel (tip of the guide pin) radiographically. Three different methods were used to define the radiological location of the drill tunnel according to Bolia et. al (3) (Fig. 5): on the medio-lateral radiograph, the position of the tip of the pin was evaluated using the 4 x 4 box grid method, as well as the percentage caudo-cranial location converted to an absolute millimeter value, identical to the preoperative planning. Moreover, the percentage disto-proximal location was measured postoperatively (dpPosPost) and compared to published data (3). On the disto-proximal radiograph the guide pin position was evaluated based on the o'clock method (o'clockPos) (3) (Fig. 5). Measurements for right stifles were converted to left stifle.

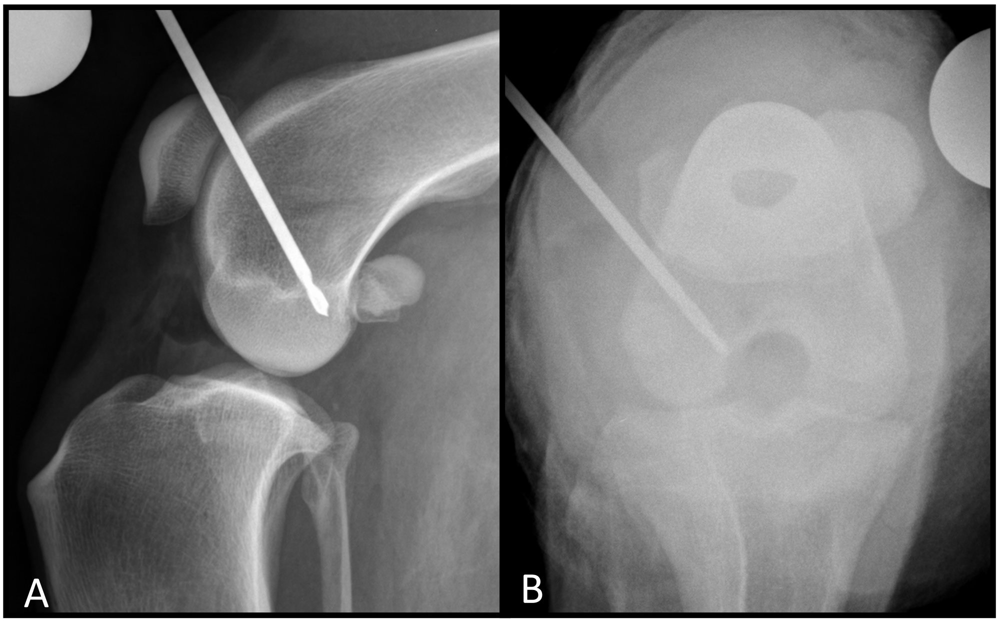

Figure 4. Typical postoperative radiographs with the guide pin left in place medio-lateral (A) and disto-proximal (B) view.

Abbildung 4. Repräsentative postoperative Röntgenbilder in 2 Ebenen während der Zieldraht belassen wurde.

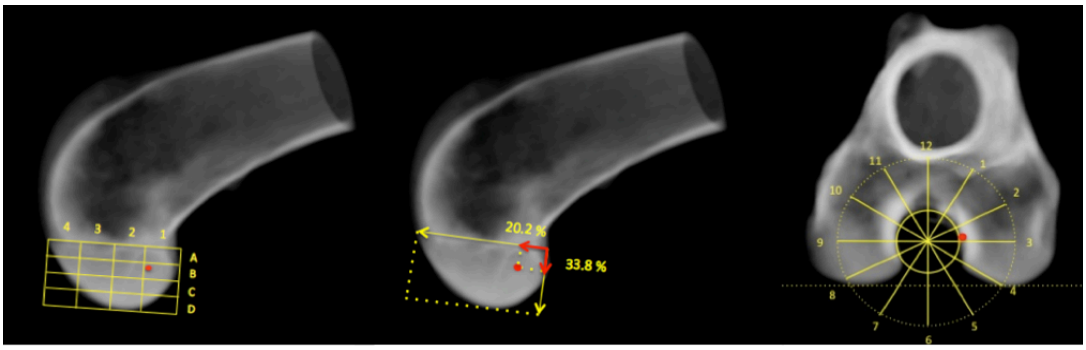

Figure 5. The radiographic location of the CrCL center on the femur as reported by Bolia et. al (3). According to the 4 x 4 box grid method the center of the CrCL is consistently located in the B1 rectangle, which represents the second rectangle from the top of the most caudal column of a box drawn over the superimposed femoral condyles. The percentage mean caudo-cranial and proximo-distal locations are 20.2 % (± 2.2) and 33.8% (± 3.7), respectively. On the disto-proximal radiograph the o'clock location is between 2 and 3 o'clock for a left femur and 9 to 10 o'clock for a right femur

Abbildung 5. Röntgenologische Lage des Ansatzes des vorderen Kreuzbands nach Bolia et al. (3). In der mediolateralen Projektion befindet sich das Zentrum des femoralen Kreuzbandursprungs im B1-Rechteck (das zweite Rechteck von proximal in der kaudalen Spalte einer Box, die über die übereinanderliegende Femurkondylen gezeichnet ist. Die Position des Zentrums wurde auch im Bezug auf die oberste und kaudalste Ecke der Box berechnet und als Prozentsatz der gesamten Länge und Höhe der Box ausgedrückt. Die mittlere prozentuale kaudokraniale und proximodistale Position beträgt 20,2% (± 2,2), bzw. 33,8% (± 3,7). Im distoproximalen Röntgenbild liegt das Zentrum des femoralen Kreuzbandursprungs zwischen 2 und 3 Uhr für linke Femora und zwischen 9 und 10 Uhr für rechte Femora.

3D estimation of tunnel position and comparison to the true anatomic CrCL insertion center

Following pin removal transverse computed tomography (CT) of the distal half of each femur and the paired femur, serving as anatomical reference, was performed using a multi-slice helical CT scanner (Phillips Brilliance, Phillips, Netherlands) with an average in-plane resolution of 0.17 mm (SD = 0.03 mm) and a slice thickness of 1 mm with an overlapping increment of 0.5 mm. Image reconstruction was done using a sharp bone filter (Filter type and Convolution Kernel D; Phillips Brilliance, Phillips, Netherlands).

Before CT scanning each paired reference femur was disarticulated at the stifle and all soft tissues except for the attachment of the CrCL on the medial aspect of the lateral condyle were removed. Afterwards, an orthopedic wire (∅ 0.4 mm) was glued (UHU® superglue, UHU, Germany) along the cranial border of the CrCL stump. This wire served as anatomic reference during segmentation of the CrCL footprint later on (3). The CT data set of the operated femur was matched onto the CT data of the paired reference femur, using 3DSlicer (v4.0, www.slicer.org). Finally, 3D surface reconstructions of each distal femur were calculated using dedicated image analysis software based on the VTK (VTK 5.2, Kitware Inc., New York, NY, USA, www.vtk.org). Because the CT data of the operated femur had been matched onto the data of the paired reference femur, both 3D models overlapped perfectly. Within Paraview (ParaView 4.2, Kitware Inc., New York, NY, USA; www.paraview.org), a sphere (∅ 2.4mm) was placed exactly at the opening of the guide pin tunnel and the 3D coordinate was recoded.

For the reference 3D model the center of the CrCL footprint was calculated according to Bolia et al. (3) and a sphere (∅ 2.4mm) was placed at these coordinates. The distance in millimeters of the coordinate of the center of the drill tunnel opening and the center of the CrCL footprint on the reference femur (distDrRef) was finally recorded (Fig. 6).

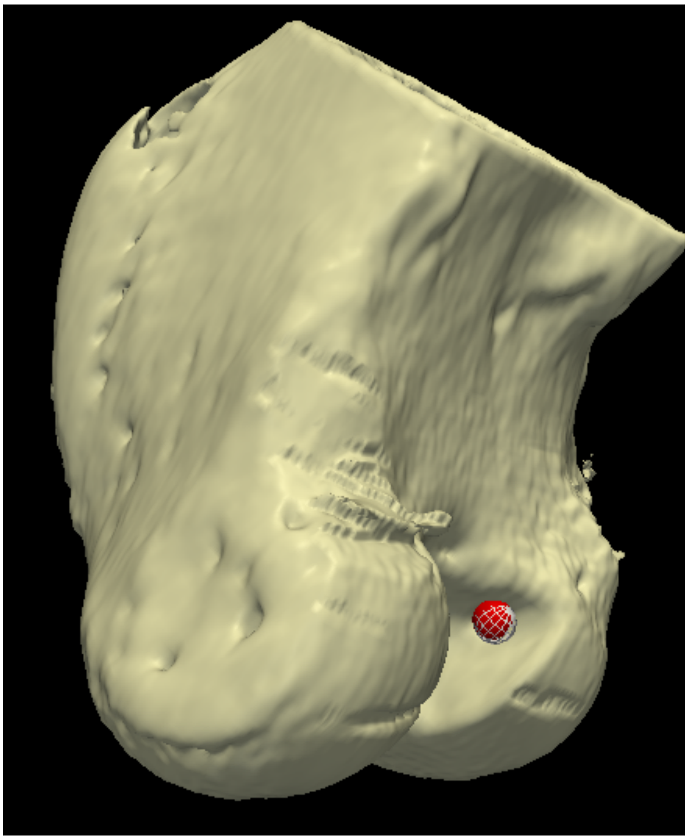

Figure 6. 3D reconstruction of a matched left and right femur. The red sphere marks the anatomical center of the reference femur, while the white sphere marks the exit point of the drilled tunnel. The distance between the two spheres represents the absolute error of drill tunnel placement (distDrRef).

Abbildung 6. 3D Rekonstruktionen nach Registrierung des rechten und linken distalen Femurs eines Hundes. Die rote Kugel markiert das anatomische Zentrum des vorderen Kreuzbandursprunges am Referenzfemur während die weiße Kugel die Bohrkanalöffnung markiert. Der Abstand zwischen den beiden Kugeln ergibt den absoluten Fehler der Bohrkanalplatzierung (distDrRef).

Estimation of ∅ 4mm drill tunnel position

After CT imaging the guide pin was reintroduced into the drill tunnel of the six operated stifles and overdrilled with a cannulated drill of 4 mm diameter. The resulting tunnel exit point was documented with a photograph of the medial aspect of the lateral femoral condyle and evaluated visually for its position within the area of the CrCL footprint and potential violation of the joint cartilage.

Data Analysis

Because of the small sample size, continuous data are expressed as median, 25% and 75% interquartile range (IQR), along with their minimal and maximal values. Values analyzed are the radiographic precalculated caudo-cranial position of the estimated drill tunnel (ccPosPre), the radiographic caudo-cranial position of the performed drill tunnel (as percentage value and millimeter value; ccPosPost), the percentage postoperative proximo-distal position (pdPosPost), the o'clock position (o'clockPos) and the distance between the center of the sphere marking the drill tunnel and the sphere marking the true anatomical CrCL center on the reference 3D model (distDrRef).

RESULTS

Radiographic measurements

Preoperative

The median absolute preoperative caudo-cranial distance (ccPosPre) was 5 mm (IQR: 5.0 to 5.4 mm; range: 4.5 to 5.5 mm) (Tab. 1).

Postoperative

The median absolute postoperative caudo-cranial distance (ccPosPost) was 5 mm (IQR: 4.4 to 5.3 mm; range: 4.2 to 6.0 mm) (Tab. 1). The median percentage ccPosPost was 19.5 % (IQR: 18.3 % to 21.5 %; range: 18 to 23 %).

According to the 4 x 4 box grid method the exit point of all six tunnels was located in the B1 rectangle

The median percentage proximo-distal position (pdPosPost) was 34.5 % (IQR: 34.0 % to 35.8 %; range: 31.0 to 39.0 %).

On the disto-proximal radiograph the o'clock position (o'clockPos) was between 2 and 3 o'clock in 4 of the 6 operated stifles and exactly at 3 o'clock in the remaining two.

Table 1. Radiographic measurements of the predicted (ccPosPre) and drilled (ccPosPost) caudo-cranial locations and their respective differences, the percentage proximo-distal location (pdPosPost) of the resulting tunnels, the postoperative o'clock position (o'clockPos), and the deviation of the drilled tunnel from the true anatomical center of each reference femur in 3D space (distDrRef) for the 6 operated stifles.

Tabelle 1. Radiologische Messungen der kalkulierten preoperativen (ccPosPre) und gebohrten postoperativen Bohrkanalposition (ccPosPost), sowie die resultierende Differenz, die prozentuale proximo-distale Lage (pdPosPost), die postoperative o'clock Position, und die dreidimensionale Abweichung vom wahren anatomischen Zentrum (distDrRef) für die sechs operierten Femora.

	ccPosPre (mm)	ccPosPost (mm)	Difference (mm)	pdPosPost (%)	o'clockPos	distDrRef (mm)
Stifle 1	5.5	5.2	0.3	35.0	3	0.9
Stifle 2	5.0	4.8	0.2	31.0	2 ½	0.7
Stifle 3	5.0	5.3	0.3	36.0	2 ½	0.5
Stifle 4	5.5	6.0	0.5	39.0	2 ½	0.5
Stifle 5	4.5	4.2	0.3	34.0	2 ½	0.2
Stifle 6	5.0	4.3	0.7	34.0	3	0.7
Median	5.0	5.0	0.3	34.5	2 ½	0.6
IQR	5.0 - 5.4	4.4 - 5.3	0.3 - 0.5	34.0 - 35.8	2 ½	0.5 - 0.7
Range	4.5 - 5.5	4.2 - 6.0	0.2 - 0.7	31.0 - 39.0	2 ¾	0.2 - 0.9

3D Measurements

The median distance between the anatomical CrCL center of the reference femora and the center of the drill tunnel opening (distDrRef) was 0.6 mm (IQR: 0.5 to 0.7 mm, range: 0.2 to 0.9 mm) (Fig. 7).

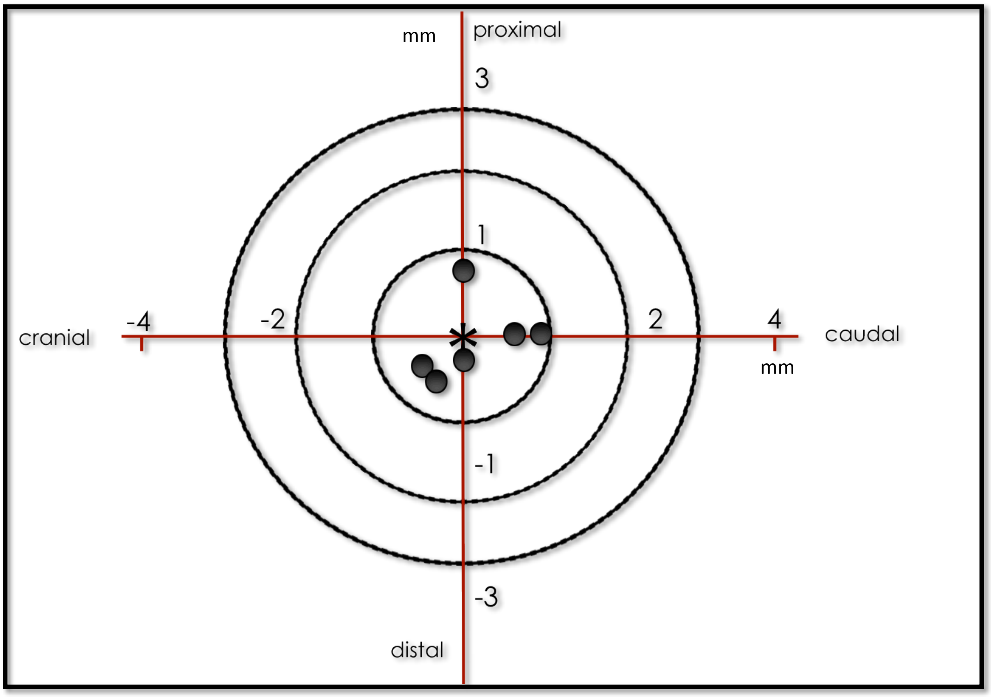

Figure 7. Absolute location of the drill tunnel positions in relation to the anatomical center of the femoral insertion of the CrCL in the 6 operated stifles expressed in millimeters. ∗, anatomical center of the CrCL; ●, drill tunnel.

Abbildung 7. Absolute Lage der Bohrkanäle in Relation zum anatomischen Zentrum des femoralen Kreuzbandansatzes für die 6 operierte Kniegelenke, in Millimeter ausgedrückt. ∗, anatomisches Zentrum des vorderen Kreuzbandansatzes; ●, Bohrkanals

4 mm Drill Tunnel

All exit holes after overdrilling to 4 mm tunnels were located within the CrCL femoral footprint (Fig. 8). Moreover neither fracturing of the lateral femoral condyle nor violation of the articular cartilage was recorded.

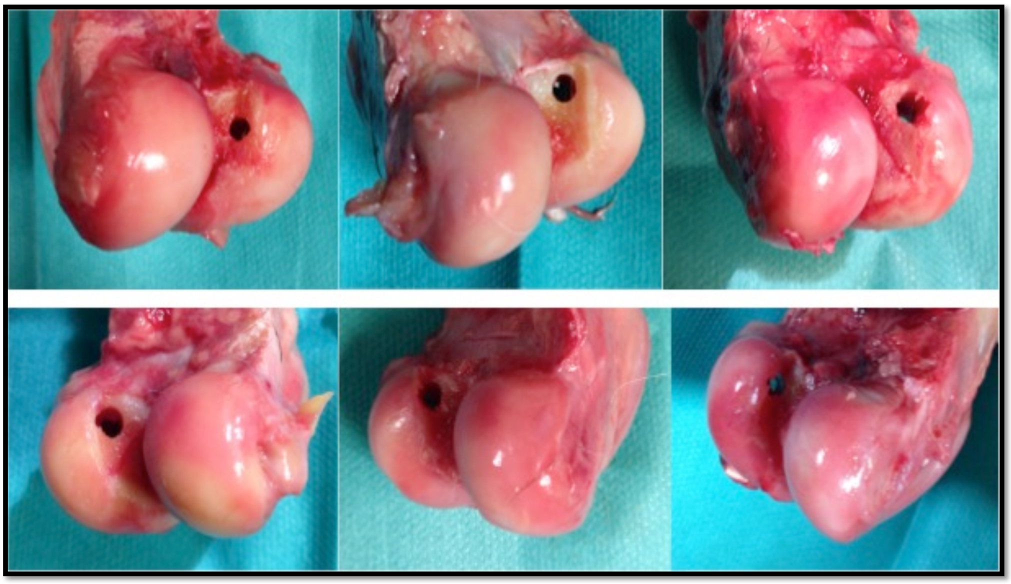

Figure 8. Photographs of the six operated femora with 4 mm tunnels Note that the exit holes of all tunnels emerge inside the CrCL footprint. Neither fracturing of the lateral femoral condyle nor violation of the articular cartilage was recorded.

Abbildung 8. Fotos der sechs operierten Femora mit 4 mm Bohrkanälen. Alle Bohrkanäle liegen innerhalb des vorderen Kreuzbandansatzes. Weder eine Fraktur der lateralen Kondyle noch Verletzungen des Gelenkknorpels wurden festgestellt.

DISCUSSION

Intra-articular misplacement of either the tibial or femoral bone tunnel opening accounts for 70-80 % of all documented technical errors in people undergoing revision for graft failure after intra-articular ACL repair (35). Misplacement of the graft in humans may cause either restricted flexion of the knee, if the graft resists the increased loads, or it may lead to elongation of the graft and subsequent failure, both resulting in recurrent joint instability (1, 12). Therefore, accurate tunnel placement appears to be, if not the most important, one of the most important technical aspects in intra-articular CrCL repair in humans but very likely also in dogs. Until now, there have been no veterinary studies proving that the misplacement of the graft has the similar effects as in people. A direct comparison cannot be made but the smaller size of the canine stifle and the different standing angle in dogs compared to humans may lead to even worse complications. Further studies are needed in order to prove this.

The reported results of this *ex vivo* study suggest that arthroscopic femoral tunnel placement can be achieved with high precision, using the newly developed aiming device in combination with a radiological estimate of caudo-cranial tunnel position. This measurement can be derived from a standard medio-lateral radiograph of the stifle, which is considered part of the diagnostic work up of every dog with lameness localized to the knee joint. In the operated 6 stifles, the resulting median error of the exit point of the femoral tunnel in comparison to the individual anatomical center of the femoral CrCL footprint was 0.6 mm, with 0.9 mm as the maximal error encountered. Therefore our working hypothesis, that femoral tunnel drilling would be possible with ≤ 1 mm error, was proven to be correct. The median difference between preoperative and postoperative caudo-cranial measurements on the medio-lateral radiographs was 0.3 mm (range: 0.2 to 0.7 mm), which is less than the median error of tunnel malpositioning based on the CT models (median: 0.6 mm, range: 0.2 to 0.9 mm). This discrepancy is probably related to the fact that a three dimensional measurements cannot directly be compared with the uni-planar measurement derived from a medio-lateral radiograph. Positioning artifacts during planar radiography could attribute as well. Nevertheless, we consider the radiographic evaluation of postoperative tunnel placement to be accurate enough for clinical application, even though surgeons should bear in mind, that plain radiography might slightly underestimate the degree of misplacement.

The results of the o'clock method reveals that the accuracy of the positioning of the drill tunnel in the proximo-distal plane was also very high. None of the tunnels were malpositioned. The disto-proximal radiograph needed for this evaluation can be easily obtained, as this projection is used to diagnose rotational deformities of the femur and therefore is considered an established radiographic method. Nevertheless, in the everyday clinical practice, in cases where this projection cannot be obtained, because of technical reasons or for the protection of the personal against radiation, proximo-distal tunnel location can also be evaluated from the medio-lateral radiograph, according to the proximo-distal percentage location (3). The median proximo-distal location of 34.5 % in the present cases, is consistent with the reported value of 33.8 % ±3.7 (3).

All six 4 mm tunnels emerged within the femoral footprint of the CrCL, which we consider a very satisfactory result. Using a diameter of 4 mm as final tunnel size is considered clinically sound, as graft placement has been reported to be done by the use of tunnels with similar size. As seen in the photographs (Fig. 8), slight misplacement of the tunnel would result in violation of the articular cartilage or blow out of the caudal wall of the femoral condyle, both scenarios leading to potential catastrophic complications. This underlines the importance of precise tunnel placement apart from the biomechanical aspect of proper graft placement during intra-articular CrCL reconstruction.

In humans, tunnel placement usually involves consistent intra-articular landmarks. Such landmarks are the intercondylar line and the cartilage-bone interface (25) but also an osseous ridge between the two bundles of the ACL, called lateral bifurcate ridge (7). In the present study intra-articular landmarks for the placement of the aiming device were also used. However, to be able to place the hook at the desired location behind the lateral femoral condyle, thorough debridement to the CrCL stump is necessary. This might limit the technique to arthroscopy, as it is uncommon to have a shaver or high frequency-unit available during arthrotomy. The second landmark, the roof of the intercondylar fossa at the base of the caudal cruciate ligament origin, is also very critical, as it defines the proximo-distal location of the tunnel within the CrCL footprint. This landmark can be easily visualized both during arthroscopy or arthrotomy. Further studies will be needed to evaluate, whether arthrotomy would allow for the same precise tunnel placement as documented in the present study using arthroscopy.

We adopted the concept of anatomic single-bundle reconstruction, using the center of the CrCL as target for tunnel placement because this approach has become the current standard in human anterior cruciate ligament surgery (16). Anatomical single-bundle CrCL reconstruction aims for restoration of the global biomechanical function of the native CrCL, and therefore tunnel positioning is performed to replicate the so-called “mid-bundle” of the native ligament, at the center of the respective footprints (1, 16). We do not consider replication of the functional heterogeneity of the native CrCL to be mandatory at this stage, as double-bundle reconstruction of the ACL has failed to provide superior clinical results than single-bundle reconstruction in men (16). Nevertheless, a persistent rotational instability during single bundle techniques remains a concern (26).

Further aspects, such as graft selection, its fixation to the bone and the ideal tension of the graft, remain to be addressed. An optimal graft for CrCL reconstruction would use a material of sufficient strength and minimum harvest morbidity, would have accurate, reliable placement and fixation, would allow immediate weight bearing and full range of motion. In human medicine autografts, allografts and synthetic materials are used. The two most commonly used autografts in ACL reconstruction are the patellar tendon autograft and the four-strand hamstring tendon autograft, consisting of the gracilis and semitendinosus tendons (8). Allografts in ACL reconstruction have advantages including decreased operative time, smaller incisions, and less post-operative pain (8). Synthetic materials, such as the LARS system (Ligament Advanced Reinforcement System, Surgical Implants and Devices, Arc-sur-Tille, France) (9), and the Leeds-Keio ligament (Neoligaments Ltd, Leeds, United Kingdom) (21) carry no donor site morbidity but foreign body reaction in combination with the high prices remain a concern. Numerous graft fixation methods such as screws, crosspins, buttons or staple/screw and washer for direct bone anchoring have been proposed. Up to now no superior method of graft fixation has been identified in humans (29).

Limitations

Several limitations may be of concern when applying this technique to clinical cases. The current study used specimens weighing ≥20 kg, because this dog population is considered to be at high risk for naturally occurring CrCL rupture (6). Therefore, we cannot comment on the use of the described technique in small or giant breed dogs.

Other limitations of the study concern the use of the aiming device. The satisfying results in the 6 cadaveric stifles might not have been achieved if an inexperienced surgeon would have performed the procedures. We strongly encourage potential users to practice on cadavers before clinical use. The repeatability and reproducibility of femoral tunnel drilling using the device has still to be proven with a larger sample size and different surgeons.

We only investigated normal stifles, with no signs of osteoarthritis. The identification of the aforementioned intra-articular landmarks and the application of the device may be more difficult in osteoarthritic joints. A thorough debridement of the osteophytes in and around the intercondylar fossa could solve this potential problem in clinical cases.

Conclusion /Clinical Relevance

Precise anatomic placement of the femoral tunnel for intra-articular repair of the ruptured CrCL was achieved using an adjustable aiming device after preoperative radiological planning. This complements the published technique for tibial tunnel drilling (33), providing the necessary technical ground for anatomic CrCL graft placement in middle to large sized dogs.

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3 Discussion

The tremendous amount of ongoing research dealing with canine CrCL pathology and the continuous development of new surgical procedures suggest that none of the existing techniques offer an excellent and objective outcome (KNEBEL and MEYER-LINDENBERG 2014). Among those numerous procedures, the intra-articular cruciate repair remains one of the least preferred, (KORVICK et al. 1994a, LEIGHTON 1999, DUERR et al. 2014) and has objectively shown to be clinically inferior compared to other methods (CONZEMIUS et al. 2005).

Our study showed that the radiographic location of the center of the femoral footprint of the CrCL can be identified in radiographs of the canine femur, serving as an essential tool for the anatomic cranial cruciate reconstruction in middle to large breed dogs. In particular, on the sagittal plane the center of the CrCL footprint is located in the second rectangle from the top of the most caudal column based on the 4x4 box grid method. The percentage caudo-cranial and proximo-distal position measured from the most caudal and proximal corner of the grid box is located 20.2 % (± 2.2) and 33.8% (± 3.7) respectively. On the transverse plane and according to the o'clock position, the center of the CrCL footprint is located between the 2 and 3 o'clock position for left femora and between the 9 and 10 o'clock position for right femora in 98% of the cases.

The hereby-reported results after using the aiming device showed that femoral tunnel placement can be achieved with high precision (<1mm) when combined with the radiological measurement. This measurement can be derived from a standard medio-lateral radiograph of the stifle and is based on the percentage caudo-cranial position of the CrCL footprint, as described in the first part of our study. All exit tunnels were located inside the CrCL footprint and there were no complications noted. In detail in our 6 specimens, the median error of the exit point of the femoral tunnel in comparison to the individual anatomical center of the femoral CrCL footprint (golden standard) was 0.6 mm, with 0.9 mm as the maximal error documented. The median percentage caudo-cranial position and proximo-distal positions were 19.5 % and 34.5 %, respectively. These values are consistent with the reported 20.2 % (± 2.2) and 33.8 % (±3.7) of our radiographic study. According to the 4 x 4 box grid method the exit point of all six tunnels was located in the B1 rectangle. Finally, the o'clock position (was between 2 and 3 o'clock in 4 of the 6 operated stifles and exactly at 3 o'clock in the remaining two.

Among graft selection, fixation method and intraarticular bone tunnel placement, in humans tunnel placement is most prone to technical errors (GETELMAN and FRIEDMAN 1999, TOPLISS and WEBB 2001, YIANNAKOPOULOS et al. 2005). As early as in 1991 it was recognized that anatomical graft placement is crucial to prevent graft failure and instability (WEISS 1991b). Considering the fact that a common human stifle is two to three times larger than a typical Labrador stifle, the high rate of technical errors in tunnel placement in men, could explain why intra-articular CrCL reconstruction in dogs showed poor clinical outcomes in the past, as we anticipate even higher rates of tunnel misplacement in canines.

Correct tunnel placement should be directed at placing the bone tunnels in an isometrical manner (PENNER et al. 1988). This ensures that there will be no change in graft length during motion and it is achieved by finding two points, one at the femur and one at the tibia that do not change their distance throughout a motion cycle (PALMISANO et al. 2002). Nevertheless, the CrCL itself is not entirely isometric (CSIZY and FRIEDERICH 2002, PETERSEN and ZANTOP 2010), although isometric zones inside the attachment sites of the ligament on the bone do exist (ZAVRAS et al. 2001). The femoral and tibial footprints are rather surfaces than points and the two bundles of the ligament behave differently during flexion and extension (ARNOCZKY and MARSHALL 1977). While the initial literature proposed reconstruction targeting graft isometry, the subsequent literature proved that the anatomical placement is crucial (PENNER et al. 1988, FLEMING et al. 1993, GAROFALO et al. 2007, ROE et al. 2008, FISCHER et al. 2010, HULSE et al. 2010). This approach is based on the replication of the true anatomy and therefore isometry of the graft similar to the native CCL by placing the tunnels as closely as possible to the anatomic position of the CCL insertions (AMIS et al. 1994). For these reasons we focused on the anatomical single bundle reconstruction. Ideally the bone tunnels are placed in the center of each insertion of the ligament to the bone (AMIS et al. 1994, KIM et al. 2013). The reconstruction of both bundles of the CrCL -known as double bundle technique- is theoretically superior by being 'more anatomic' compared to the single bundle technique. Moreover the different behavior of the two distinct bundles is an indicator that double bundle reconstruction may be superior. This technique has not yet been performed or investigated in dogs but human studies are controversial (AHLDEN et al. 2013, BJORNSSON et al. 2013). Recently, several biomechanical studies showed that the single bundle ACL grafts placed in the center of the anatomic insertions of the ACL succeed in providing nearly normal knee kinematics comparable to double bundle reconstruction (RUE et al. 2008, STEINER et al. 2009, ARAKI et al. 2011). A persistent rotational instability during single bundle techniques remains a concern (PORTER and SHADBOLT 2014). Nevertheless, a recent study showed that the double bundle technique was not more effective in preventing osteoarthritis (SONG et al. 2013). Some reported additional advantages of the single bundle technique are the fact that is not that technically demanding as the double bundle, the revision surgery is considered easier, appears to be less painful for the patient post-operatively (MACDONALD et al. 2014). The drilling of two tunnels in the lateral femoral condyle of a dog could cause damage to the articular cartilage or in worst cases fractures of the distal femur. This fact has been also confirmed from our results, where a small misplacement of the tunnel could easily lead to trauma of the articular cartilage. Whether a single or double bundle reconstruction in dogs is technically feasible and could provide with better clinical outcomes has to be investigated in the future.

In order to be able to perform an accurate tunnel drilling, knowledge of the ‘target’ is a prerequisite. The radiographic location of the center of the CrCL femoral footprint in large breed dogs has not been reported extensively in the veterinary literature. The only study addressing this subject in dogs cannot be directly compared to our investigations (REICHERT et al. 2013). As already discussed in our first publication the different methodology of the studies might explain the discrepancies. The center of the femoral footprint of the CrCL in our study is calculated in 3D space, while the measurements of Reichert et al. are based on a uniplanar projection of the footprint on a mediolateral stifle radiograph. We used the Blumesaat’s line as a reference for drawing the 4x4 grid box. The width of the grid box is defined by the most cranial and caudal border of the condyles and not by the length of the Blumensaat’s line, as done in the Reichert study. The proximo-distal location on the other hand was measured using the same landmarks as in the study of Reichert et al., but their results are different to what we documented (46.6 % vs. 33.8% in the current study). This discrepancy might be attributed to the fact that the sample size of the Reichert study is small (12 vs. 49 limbs in the current study). Moreover, we did not use paired femora in the anatomic study, which contributed to a more heterogenic population. Another significant difference between both studies is dog size, with our specimens belonging bigger dogs (12.9 – 26.2 kg vs. 20.3 – 57.0 kg in the current study).

The location of the center of the CrCL on radiographs is a fundamental tool during intra-articular reconstruction. Not only is it valuable for the pre-operative planning but it is also very important for the control of the tunnel location intra- and post operatively. Finally this, individual for each dog, measurement was necessary for the development of the adjustable aiming device.

Femoral tunnel drilling has been rarely performed in dogs and when done, it was free handed (PAATSAMA 1952, PUNZET and WALDE 1974, BISKUP et al. 2015, COOK et al. 2015). In the veterinary literature no aiming device for drilling of femoral tunnel for the intra-articular CrCL in dogs has been reported so far. The aiming device we used (modified KYON aiming device, KYON, Switzerland) consists of a drill sleeve, a hook and a handle connecting these two components. The hook can be moved along its central axis, allowing for adjustment of the caudo-cranial offset of the resulting drill tunnel. The hook made the introduction of the individualized radiological measurement possible, improving the precision of the technique. The concept of individualized reconstruction is used in people too (HOFBAUER et al. 2014). The caudo-cranial location, calculated from a medio-lateral stifle radiograph, can be easily converted to millimeters and introduced to the device. The fact that a guide pin is used before drilling the final tunnel has the advantage the correct location can be verified with fluoroscopy, a technique routinely used in people (TOPLISS and WEBB 2001, PASSLER and HOHER 2004), and directly corrected if the end of the pin is not located in the desired position inside the CrCL footprint. The disto-proximal location of the tunnel is based on anatomical landmarks, which makes the placement of the device more consistent.

Apart from the use of the aiming device the difficulty level of the intra-articular cruciate reconstruction in dog is considered high at the moment. The use of intra-articular landmarks referred in the second publication can significantly ease the technique are reduce tunnel misplacement. In humans the use of such landmarks is routine (FINEBERG et al. 2000, FERRETTI et al. 2007, PETERSEN et al. 2013). Moreover the surgeon's experience with arthroscopy is necessary. We also advise the use of an arthroscopic bevel for the debridement of all the CrCL stump remnants and improvement of visibility inside the intercondylar fossa. It is possible that the identification of the necessary landmarks is limited in stifles with DJD. For this reason, the use of the reported aiming device in the future has to be tested in cases with CrCL rupture and secondary osteoarthritic changes. A thorough debridement of the osteophytes could resolve this problem and optimize visualization. This procedure is called notch plasty (TOBIAS and JOHNSTON 2011). Finally anatomical variations should be taken into account before using the aiming device, as they could lead to misplaced tunnels.

Aspects of the intra-articular CrCL reconstruction in dog that are in need of further investigation are the selection of the graft, its fixation method on the bone and the appropriate graft tensioning. The two most commonly used autografts in ACL reconstruction are the patellar tendon autograft and the four-strand hamstring tendon autograft, consisting of the gracilis and semitendinosus tendons (FU et al. 1999). The most common reported autograft materials for canine CrCL reconstruction are the patellar tendon and fascia lata (ARNOCZKY et al. 1986a, PATTERSON et al. 1991). The double flexor tendon and the bone patellar tendon have also been described and evaluated in dog cadavers (TOMITA et al. 2001). Allografts in human ACL reconstruction have been reported to have certain advantages such as decreased operative time, smaller incisions, and less post-operative pain (FU et al. 1999). Various allografts in dogs have also been used in experimental studies (CURTIS et al. 1985). In a recent *in vitro* canine study allografts with different fixation methods were mechanically tested (BISKUP et al. 2015). The deep digital flexor tendon (DDFT) allograft secured with transverse femoral fixation and stabilized with a tibial interference screw and 2 spiked washers on the tibia showed similar mechanical properties as the native CrCL (BISKUP et al. 2015). Generally the use of the deep digital flexor tendon as an allograft is gaining popularity in dogs and it could be a viable option for testing *in vivo* (BISKUP et al. 2015, COOK et al. 2015). In a study comparing allografts and autografts in dogs, allografts showed increased synovial leukocyte counts, joint cartilage erosion, decreased strength and metabolic activity of the grafts itself and evidence of an immune response. These findings indicate that allografts may me problematic in dogs (THORSON et al. 1989). In humans autografts are still preferred because allografts carry the possibility of disease transmission (FU et al. 1999). Modern synthetic materials, such as the LARS system (GATINEAU et al. 2010) (Ligament Advanced Reinforcement System, Surgical Implants and Devices, Arc-sur-Tille, France), and the Leeds-Keio ligament (MATSUMOTO and FUJIKAWA 2001) (Neoligaments Ltd, Leeds, United Kingdom) carry no donor site morbidity but issues as cell viability and foreign body reaction in combination with the high prices remain a concern (LEGNANI et al. 2010). These materials have also been used in dogs (LEDUC et al. 1999, MATSUMOTO and FUJIKAWA 2001). Materials such as dacron, polyester, polyamide and polyglycolic acid have been tested in dogs during the past decades (CABAUD et al. 1982, ARNOCZKY et al. 1986b, DE ROOSTER et al. 2001). At the moment there is one commercial available synthetic ligament for dogs made from polyethylene terephthalate (PET) (STIF Ligament, Vetlig, France). Nevertheless further *in vivo* studies are needed in order to investigate their clinical performance.

Numerous graft fixation methods such as interference screws, cross-pins, buttons or staple/screw and washer for direct bone anchoring have been proposed (LETSCH 1994, LOPEZ et al. 2003, TOBIAS and JOHNSTON 2011, BISKUP et al. 2015). In the only veterinary report comparing fixations methods, transverse femoral fixation combined with a tibial interference screw showed excellent mechanical properties (BISKUP et al. 2015). The transverse femoral fixation and a secondary fixation of the graft after coming out of the bone tunnels are strongly suggested from the authors (BISKUP et al. 2015). Up to now no superior method of graft fixation has been identified in humans (HOHER et al. 2003, TECKLENBURG et al. 2005, SPEZIALI et al. 2014).

The influence of graft tensioning in dogs has not been yet investigated. In humans tension has shown to be critical (AMIS 1989). Small errors caused subluxation of the joint, inhibiting of joint extension and failure of the implant (AMIS 1989). For example, in humans a tension around 80 N is considered ideal for hamstring–polyester grafts (ARNEJA et al. 2009, KIRWAN et al. 2013). Nevertheless no clear suggestions, neither the human literature nor in the veterinary, regarding tension and no clinical relevant tension regimes when using biologic or synthetic materials currently exist. Overall there is insufficient evidence to conclude whether patient-specific function is improved at any specific tension (FLEMING et al. 2013, KIRWAN et al. 2013). Even in humans more randomized studies and the testing of different materials are needed. The use of tensioners in dogs has been described (TOBIAS and

JOHNSTON 2011, BISKUP et al. 2015) but the effect of tension of the different kinds of grafts has to be tested when the intra-articular cruciate repair in dogs becomes technically available.

The results of this *in vitro* study in dogs suggest that arthroscopic femoral tunnel placement can be achieved with high precision, using the aiming device in combination with a radiological measurement. The cornerstone of anatomical cranial cruciate repair was finally laid. In combination with the study of Winkels et al. (WINKELS et al. 2010a, WINKELS et al. 2010b) the minimally invasive drilling of bone tunnels under arthroscopic control is now possible. After the *in vivo* testing of the commercially available grafts and fixation methods, an improvement of clinical outcomes will hopefully soon become reality.

4 Summary

Bolia Amalia

Anatomic intra-articular reconstruction of the cranial cruciate ligament in dogs: The femoral tunnel

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(65 pages, 17 figures, 1 table, 141 references)

Keywords: cranial cruciate ligament rupture, stifle, dog, intra-articular cranial cruciate ligament reconstruction, femoral drill tunnel

Objective: Cranial cruciate ligament (CrCL) pathology is the most frequent cause of lameness in dogs. In contrast to human medicine, where anatomic reconstruction of the ACL is considered the treatment of choice, intra-articular repair in dogs is not commonly performed and until now has not met with enduring success. Accurate tunnel placement has been shown to be crucial in obtaining a successful outcome after anterior cruciate ligament reconstruction in humans. The first aim of our study was to define the radiographic location of the center of the femoral attachment of the CrCL in dogs, for the pre-operative planning as well as post-operative control of anatomical placement of the femoral tunnel. Second aim of the study was to develop and validate an aiming device for arthroscopic femoral tunnel placement.

Materials and Methods: A. Radiographic study: Using femora from 49 adult, orthopedically sound dogs (BW ≥ 20 kg), a radiopaque marker was placed on the cranial border of the femoral footprint of the CrCL. Computed tomography and 3D reconstruction of each femur was performed subsequently, followed by manual segmentation of the footprint on the 3D models and calculation of its center. Finally, virtual digital radiographs in two planes were produced and the location of the calculated center of the CrCL was expressed using three different methods (4x4 box grid method and percentage position for the medio-lateral projection; o'clock position for the disto-proximal projection). B. Aiming device: Hindlimbs (n=12) of 6 cadaveric dogs weighing ≥20 kg were

used. One hindlimb from each cadaver was randomly chosen and the caudo-cranial position of the CrCL center was calculated, on standard medio-lateral stifle radiographs, and transferred onto to an adjustable aiming device. During stifle arthroscopy the aiming device was inserted and guide pin placed from extra-to-intra-articular. The position of the resulting bone tunnel was evaluated on stifle radiographs and also compared with the anatomic center of each contralateral hindlimb, in the three dimensional (3D) space.

Results: A. Radiographic study: In the medio-lateral radiographs the center of the femoral footprint was consistently located in the second rectangle from the top of the most caudal column of the 4x4 grid. The mean percentage caudo-cranial and proximo-distal location was 20.2% (± 2.2) and 33.8% (± 3.7), respectively. In the disto-proximal radiograph, the o'clock position of the CrCL center was between 2 and 3 o'clock in 97.6% of the femora. B. Aiming device: According to the postoperative radiographs, the location of all 6 intra-articular tunnel openings was consistent with the results of the radiographic study. In 3D space, arthroscopic femoral drilling resulted in a median deviation of the drill tunnels of 0.6 mm around the CrCL center. All tunnel openings were located within the CrCL insertion.

Conclusions: The reported data can be used to plan and verify the placement of the femoral tunnel opening during intra-articular anatomic CrCL repair. The use of the aiming device suggests that arthroscopic femoral tunnel placement can be achieved with high precision. The measurement for the device can be derived from a standard medio-lateral radiograph of the stifle, which is part of the diagnostic work up of every dog with lameness localized in the stifle. The proposed technique may reduce femoral tunnel misplacement when performing intra-articular CrCL repair in dogs. In combination with the described technique for arthroscopic tibial tunnel drilling, arthroscopic assisted anatomic reconstruction of the CrCL in dogs can be achieved.

5 Zusammenfassung

Bolia Amalia

Anatomische intra-artikuläre Rekonstruktion des vorderen Kreuzbandes beim Hund: Der femorale Bohrkanal

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(65 Seiten, 17 Abbildungen, 1 Tabelle, 141 Literaturangaben)

Schlüsselwörter: Vorderer Kreuzbandriss, Kniegelenk, Hund, intraartikulärer Kreuzbandersatz, femorale Bohrung

Zielstellung: Die Ruptur des vorderen Kreuzbandes (VkB) ist die häufigste Ursache einer Lahmheit beim Hund. Im Gegensatz zu der Humanmedizin, wo die anatomische intraartikuläre Rekonstruktion des vorderen Kreuzbandes als Therapie der Wahl gilt, wird die intraartikuläre Rekonstruktion beim Hund nur selten durchgeführt und hat bis jetzt nicht dauerhaften Erfolg. Die anatomische Platzierung der Bohrkanäle ist bei Menschen für den Erfolg der Operation bei Menschen entscheidend. Erstes Ziel der Studie war die Bestimmung der radiologischen Lage des Zentrums des femoralen vorderen Kreuzbandursprungs beim Hund. Zweites Ziel war die Entwicklung und Erprobung eines Zielgerätes für die arthroskopisch-assistierte, anatomische vordere Kreuzbandrekonstruktion beim Hund.

Material und Methode: *A. Radiologische Studie:* Die kraniale Begrenzung des femoralen Ursprungs des vorderen Kreuzbandes (VK) wurde mit einem röntgendichten Draht bei 49 Femora orthopädisch gesunder Hunde (KM > 20 kg) markiert. Anschließend wurde eine Computertomographie und 3D-Rekonstruktion jedes Femurs angerfertigt, anhand derer der Ursprung manuell segmentiert und das Zentrum berechnet wurde. Schließlich wurden, basierend auf den 3D-Modellen, virtuelle Röntgenbilder in zwei Ebenen berechnet. An diesen wurde die Position des berechneten Zentrums mit drei unterschiedlichen Methoden bestimmt (4x4-Gitterbox-Methode und prozentuale Position für die medio-laterale Projektion; Ziffernblattmethode für die disto-proximale Projektion). *B. Zielgerät:* Hintergliedmaßen (n = 12) von 6

Hundekadavern (KM ≥20 kg) wurden verwendet. Eine Gliedmaße jedes Kadavers wurde zufällig ausgewählt und die kaudo-kraniale Lage des Zentrums des vorderen Kreuzbandansatzes (vKBA) in medio-lateralen Röntgenbildern berechnet und anschließend auf ein justierbares Zielgerät übertragen. Unter arthroskopischer Kontrolle wurde das Zielgerät hinter der lateralen Kondyle eingehakt und ein Steinmann Pin von extra nach intraartikulär platziert. Die Position der resultierenden Bohrkanäle wurde sowohl röntgenologisch bestimmt als auch dreidimensional mit dem anatomischen Zentrum des vKBA der kontralateralen Hintergliedmaßen verglichen.

Ergebnisse: *A. Radiologische Studie*: In der medio-lateralen Projektion befand sich das Zentrum des femoralen Kreuzbandursprungs im zweiten Rechteck von proximal in der kaudalen Spalte. Die mittlere prozentuale kaudo-kraniale und proximo-distale Position war 20,2 % (± 2,2), beziehungsweise 33,8% (± 3,7). Im disto-proximalen Röntgenbild lag in 97,6 % der Femora das Zentrum des femoralen Kreuzbandursprungs zwischen 14:00 und 15:00 Uhr. *B. Zielgerät:* In allen postoperativen Röntgenaufnahmen lagen die sechs Bohrkanäle im bzw. nahe dem Zentrum des vKBA. Die 3D-Messungen ergaben eine mediane Abweichung der Bohrkanalposition im Vergleich zum anatomischen Zentrum der kontralateralen Seite von 0,6 mm (Bereich:0,2– 0,9 mm).

Schlussfolgerung: Die erarbeiteten Referenzwerte können für die Planung sowie die intra- und postoperative Kontrolle der femoralen Bohrung verwendet werden. Die Verwendung eines justierbaren Zielgerätes ermöglicht die präzise anatomische Platzierung des femoralen Bohrkanals für die intraartikuläre Rekonstruktion des vorderen Kreuzbandes. Die beschriebene Methode wird helfen, eine Fehlplatzierung des femoralen Bohrkanals im Zuge der intraartikulären vorderen Kreuzbandplastik zu reduzieren. In Kombination mit dem bereits beschriebenen tibialen Zielgerät sind nun die technischen Voraussetzungen für die arthroskopisch-assistierte anatomische vordere Kreuzbandplastik in der Tiermedizin gegeben.

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